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Volume I: Final Report

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Volume I
Final Report

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16. ABSTRACT

This two-volume report provides long-term information on the release of gaseous and liquid contaminants to the biosphere from decomposing, landfilled, municipal solid waste. Volume I, the comprehensive final report, presents results from a 6-year study.

The investigation included studies of leachate migration, the relationship between contaminant concentration and leachate volume, field capacities for various sizes of milled refuse, influence of density and depth on leachate pollutant concentrations, and the relationship of leachate chemical components to each other and to leachate volume.

Volume II contains supplemental studies on stabilization and leachate behavior, including results from an additional year of groundwater monitoring at the field site.

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INVESTIGATION OF SANITARY LANDFILL BEHAVIOR
Volume I. Final Report

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solving, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

This two-volume report provides long-term information on the release of gaseous and liquid contaminants to the biosphere from decomposing, landfilled, municipal solid waste. Volume I, the comprehensive final report, presents results from a 6-year study. (Preliminary results were published in 1971 - A.A. Fungaroli, Pollution of Subsurface Water by Sanitary Landfills. Report No. SW-12rg, U.S. Environmental Protection Agency, Washington, D.C., 1971.) Volume II contains supplemental studies on stabilization and leachate behavior, including results from an additional year of groundwater monitoring at the field site.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

This two-volume study was conducted to predict landfill life through the characterization of gas and leachate generation and pollutant removal. Factors that affect stabilization of the decomposing solid waste were also studied.

The experimental facilities consisted of a sanitary landfill field site for studying gas generation, leachate migration, and groundwater contamination; a laboratory lysimeter for recording leachate quantity and pollutant removal; mini-lysimeters to determine the effect of shredding the refuse; and accelerated column tests for predicting long-term landfill behavior and for identifying the influence of depth and added nutrients on stabilization.

A two-dimensional model of leachate migration patterns was developed. The correlation between the computer solutions to the model and average field concentrations obtained from shallow wells at the field site was good. A zone of contamination in the groundwater was described.

The final report (Volume I) identifies a semi-log linear relationship between contaminant concentrations and leachate volume after field capacity is reached. The supplemental study (Volume II) confirms this relationship.

Field capacities for various sizes of milled refuse are determined along with the influence of density (and depth) on leachate pollutant concentrations. Each chemical component of leachate is positively or negatively correlated with every other chemical component as well as with the volume of leachate.

This report was submitted in fulfillment of Research Grants R800777 and R801947 by Drexel University under the sponsorship of the U.S. Environmental Protection Agency. The two-volume report covers the period September 1967 to October 1974.

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SECTION 1

INTRODUCTION

In an attempt to minimize health and pollution hazards, due to the disposal of solid waste by landfilling, sanitary landfill design criteria have evolved which are primarily empirical in nature and which may or may not have a relationship to environmental conditions(1,2). Several studies of sanitary landfill behavior have been undertaken in recent years to better understand them and to delineate and define significant design criteria. Unfortunately, many of the results obtained from these studies(6-12), most of which were limited in scope, reflect only local conditions and cannot be easily extrapolated outside the specific region.

The study described in this report was undertaken by Drexel University in cooperation with the Pennsylvania Department of Environmental Resources. Interest on the part of the Pennsylvania Department of Environmental Resources has been stimulated by its concern with the decreasing availability of suitable landfill sites within the state and the increasing frequency of pollution and health problems resulting from solid waste disposal.

The study, as conceived, was to provide quantitative information as to the behavior of sanitary landfills in an environment common to southeastern Pennsylvania, and in fact, to a large portion of the region extending between Washington, D.C. and Boston, Massachusetts. To suppress local environmental influences, the study was developed so as to generalize results, except those specifically related to the southeastern Pennsylvania region.

The long-range objectives were:

> To provide means for predicting the movement of pollutants in subsurface regions under existing and proposed sanitary landfill sites.
>
> To develop hydrologic, geologic and soil criteria for the evaluation of site suitability for sanitary operations, and
>
> To appraise design methods and remedial procedures for reducing any undesirable contaminant movement.

In general, the objectives of the study have been met and the results are presented herein. In addition, there now exist several technical publications(13,14,15,16) which address the principal objectives. Further, several studies were generated as spinoff of this investigation and the reports include:

Steiner, R. L., Chemical and Hydraulic Characteristics of Milled Refuse, Ph.D. Dissertation, Drexel University, Philadelphia, Pa. 1973.

Metry, A. A., Mathematical Modeling of Pollutant Migration in an Unconfined Aquifer, Ph.D. Dissertation, Drexel University, Philadelphia, Pa., 1973.

Zison, S. W., Effects of Heavy Metal Toxicants on Potential Decomposition Phenomena in a Simulated Solid Waste System, Ph.D. Dissertation, Drexel University, Philadelphia, Pa. In progress.

The most significant results of this study are summarized in the Summary and Conclusions section. Engineers interested in developing a sanitary landfill should find the results of great assistance.

SECTION 2

SUMMARY AND CONCLUSIONS

This report presents the results of a study of sanitary landfills under controlled laboratory and natural field conditions. Also presented are the results of a study of shredding and its effect on landfill behavior. The overall objective of this study was to provide information as to how sanitary landfills behave during their active period of degradation. A second objective was to obtain specific data so as to permit the establishment of design parameters for new sanitary landfills and to suggest remedial actions for existing sites.

The laboratory sanitary landfill was contained in a lysimeter, which consisted of a fiberglass-lined steel tank, thirteen (3.96 m.) high and six feet (1.83 m.) by six feet (1.83 m.) in cross-section. A bottom collection trough was used to collect the landfill-generated leachate. The top of the lysimeter was closed and temperatures and water input were adjusted on a pre-determined schedule. The lysimeter vertical sidewalls were insulated to minimize heat exchange with the laboratory proper, while the bottom of the lysimeter was held at a constant temperature. Essentially, the lysimeter functioned as a closed system which permitted the contained landfill to be representative of the center of a large sanitary landfill, the depth of which was small in comparison to its areal extent.

Lysimeter leachate and gas samples were analyzed, and the temperatures were monitored on a routine basis. While information on gases and temperatures was not essential to attainment of project objectives, the collection was necessary to obtain a complete picture of the behavior of sanitary landfills.

The field facility consisted of a 50 foot (15.24 m.) by 50 foot (15.24 m.) site with eight feet of refuse and a two foot (.61 m.) soil cover. Temperatures, gases and leachate quality within the landfill, as well as temperatures, gases and leachate quality outside the landfill, were collected on a routine basis. Also monitored were precipitation and ground water quality, both under and away from the landfill site.

The shredded refuse study was performed using fifty-five (55) gallon (208 l.) drums. The drums were housed in a large temperature controlled room. Refuse size and density for the study varied over a wide range so as to permit a complete evaluation of parameter significance.

LYSIMETER

The lysimeter study spanned approximately a five year period. During that time a virtually complete sanitary life cycle pattern was developed. The following have been concluded from the data generated during the lysimeter sanitary landfill life.

1. The laboratory sanitary landfill lysimeter was characteristic of a sanitary landfill with low density. However, the patterns developed are similar to those of any sanitary landfill if proper density and time adjustments are made.

2. Once an entire sanitary landfill system is brought to field capacity, the generation of leachate bears a direct relationship to the volume of water added to the system. During periods of low leachate production, any additional decrease further reduces or eliminates leachate production. Conversely, as water input increases, leachate production also increases. This phase relationship exists even when the system is not at field capacity.

3. Delays in initial leachate generation depend on

    (a) the initial moisture content of the various sanitary landfill components

        1. the lower the landfill initial moisture content, the longer the time before the initial appearance of significant quantities of leachate.

    (b) the landfill density

        1. the higher the landfill density, the longer the time before the initial appearance of significant quantities of leachate.

    (c) the rate of site filling

        1. the quicker a site is filled, the longer the time elapse before the initial appearance of significant quantities of leachate.

(d) the quantity of water infiltration

1. the lower the quantity of water infiltration, the longer the time before the initial appearance of significant quantities of leachate.

Leachate production can be attributed to one or all of the following sources:

(a) the refuse
(b) channeling
(c) an advanced wetting front
(d) a main wetting front

From the results of this study, it is concluded that the refuse, source (a), and channeling, source (b), are responsible for leachate collected from a landfill during the early time period when the landfill has been placed at a relatively low initial moisture content. Once the system reaches field capacity, leachate contributed by these sources are primarily due to the advanced wetting front, source (c). Finally, when the system reaches field capacity, leachate production is due to movement of the main wetting front, source (d).

A landfill system whose refuse and soil components are placed at field capacity would produce leachate immediately, and the source is primarily the main wetting front. One effect of these various leachate generation patterns is to alter the leachate composition. By applying basic chemical and biological kinetics, it is apparent that leachate produced during the slow attainment of the system field capacity will exhibit initial pollutant concentrations different from a landfill in which substantial quantities of leachate are produced immediately. Once the system transients have been eliminated, both landfills should produce similar, but not necessarily identical, leachates.

4. No single leachate chemical component bore a linear correlation to all the other chemical components. However, during the start-up period of the sanitary landfill lysimeter (before landfill field capacity is reached), hardness appeared to have a good linear relationship to a majority of the other chemical components. Therefore, during early periods of a sanitary landfill's development, hardness can provide a reasonable indication of whether or not leachate migration is occurring.

5. The results of the laboratory lysimeter sanitary landfill test led to the following conclusions concerning the most significant parameters:

(A) pH - Leachate solutions were generally acidic, ranging between 5.0 and 7.0. During the early life of the landfill, variations were the largest and most erratic. Early pH values ranged between 4.5 and 8.3, with the basic values occurring during low leachate flow periods. During the latter portion of the test period, pH values averaged around 6.5 with the overall trend being toward a pH of 7.0. In general, generation of large quantities of acidic leachate intensify the liquid pollution potential because low pH values reduce exchange capacities of renovating soil at the time when leachate quantities are high.

(B) Iron - Leachate volume had a significant influence on iron concentration. During low leachate quantity periods, iron concentration was relatively low; when leachate quantities were high, there was a significant increase in iron concentration. Iron concentration exceeded 1600 mg/l during the early periods of high leachate volume. Thereafter, a generally decreasing trend in concentration existed. During the last portion of the test period, iron concentration was less than 200 mg/l and decreasing.

(C) Zinc - Significant zinc removal was limited to the portion of the study which corresponded to the first period of high leachate generation. This occurred during the second year of the study. During this period, concentration peaks reached 135 mg/l. After the one period of high zinc removal, zinc concentration was negligible.

(D) Phosphate - Some phosphate was present with maximum concentrations of 130 mg/l during the early portion of the test. Thereafter, concentration levels were markedly lower and irregular. No specific pattern appeared to exist.

(E) Sulfate - Results obtained were inconclusive and the sulfate analysis was terminated early in the study.

(F) Chloride - Highest chloride concentrations occurred during the early portion of the test period. Concentrations reached as high as

2400 mg/l. Over most of the test period, concentrations ranged between 300 and 600 mg/l. However, during the latter portion of the study, concentrations were less than 200 mg/l.

(G) Sodium - Concentrations generally ranged between 500 and 1000 mg/l with an early peak of 3400 mg/l. During the latter portion of a landfill's life, concentration levels were negligible.

(H) Nitrogen - Organic nitrogen concentrations range between 50 mg/l and 200 mg/l initially, were less than 100 mg/l after two years, and were negligible during the latter portion of a landfill's life.

(I) Hardness (as $CaCO_3$) - Maximum hardness concentrations were 5500 mg/l during the first year after placement. Usually concentrations did not exceed 1500 mg/l with values less than 400 mg/l toward the end of the fifth year.

(J) Chemical Oxygen Demand - The most frequent concentration range was between 20,000 mg/l and 25,000 mg/l with an early peak in excess of 50,000 mg/l. Toward the end of the fifth year, COD concentrations were less than 2000 mg/l.

(K) Total and Suspended Solids - Maximum total solids were 40,000 mg/l immediately after placement. Usual concentrations ranged between 20,000 mg/l and 25,000 mg/l during the first two years. During the latter part of a landfill's life, total solids were less than 10,000 mg/l with values less than 1000 mg/l at the end of the fifth year. Suspended solids were very irregular with most concentrations between 400 mg/l and 1000 mg/l. An early peak of 1800 mg/l occurred immediately after placement, while concentrations of less than 100 mg/l occurred near the end of the fifth year.

(L) Nickel - Nickel concentration was very low, usually between 0.2 mg/l and 0.3 mg/l with localized peaks of 0.8 mg/l and 1.0 mg/l.

(M) Copper - Maximum copper concentration peaked at 4.7 mg/l and 9.8 mg/l early in the test. Generally, concentration levels were less than 1.0 mg/l.

Six test parameters were discontinued during the test period. Three of these, Nickel, Copper, and Dissolved Oxygen, were discontinued due to concentrations below the detectable limit of the test procedure being used. Three others, Phosphate, Sulfate, and Biochemical Oxygen Demand(16), were discontinued due to a lack of confidence on the reliability of the test procedure.

6. The lysimeter sanitary landfill temperature pattern was characteristic of a low density relatively dry refuse. Within ten days after refuse placement, temperatures reached 150°F at the center. Temperature at adjacent levels was lower. However, with time, there was a general spreading of temperature from the refuse center to the top and bottom temperature controlled boundaries.

The temperature pattern was probably unique to this particular system; that is, a young, low-density, rapidly placed, dry landfill. However, the pattern is representative of a refuse which undergoes initial high aerobic activity. It is probable that with other placement conditions, temperature peaks would occur at different refuse levels, at different times, and with different maximums. Maximums greatly in excess of the 150°F range experienced in this study should not be expected.

Lysimeter temperatures stabilized at approximately 80°F, approximately 60 days after refuse placement. The general temperature pattern obtained indicated that the refuse was initially in a general aerobic state, and that after 60 days, an anaerobic condition became dominant.

After the refuse temperatures became virtually steady-state, that is, when the refuse becomes anaerobic; changes in top boundary temperatures had little influence on internal temperature levels or distribution. The behavior implies that alteration of internal temperatures, due to changes in environmental temperatures, are minimized by the soil and refuse insulating properties, as well as by changes in biological activity. The net result of all temperature influences is a virtually constant internal temperature state.

7. Gas samples taken from four levels within the laboratory sanitary landfill lysimeter were analyzed for carbon monoxide, hydrogen sulfide, nitrogen, carbon dioxide and methane. No carbon monoxide or hydrogen sulfide was detected.

The general pattern of methane concentration was an increase with depth. The samples closest to the top of the refuse showed very little methane (usually less than 5 percent), while with increasing depths concentrations increased.

Significant quantities of methane began to appear approximately one hundred (100) days after placement. Oxygen, although of low quantity, was detectable at all depths over the entire life of a landfill. Carbon dioxide was present over the entire test period in amounts which increased slightly with depth.

8. Methane concentrations initially increased with depth and time. Most methane concentrations ranged between twenty (20) and thirty (30) percent. Peak concentrations of forty (40) percent occurred at 6 feet (1.83 m.) below the top of the refuse and of thirty (30) percent at 8 feet (12.44 m.) below the top of the refuse.

9. Methane was at maximum at all levels during the second and third years of a landfill's life. While local increases in methane occurred toward the end of the fifth year, peaks were significantly less than previously detected. Further, the general trend of concentrations was decreasing.

10. From the temperature data, after the initial transient condition, the temperatures decreased and were virtually non-varying. The temperature data indicates the existence of an anaerobic state within the refuse after the initially high temperatures. However, the gas data, particularly the continued existence of oxygen, indicates that aerobic pockets also existed in the refuse even at the deeper regions. Therefore, it is possible to have aerobic and anaerobic activity existing simultaneously within the refuse.

11. The results of this study indicate that gas generation patterns are more indicative of the landfill age than temperature.

12. A final analysis of the refuse removed from the lysimeter indicated that over the test period (5 years) somewhere between seventy-five (75) and ninety (90) percent of the water soluble components have been removed from the refuse. (See Table 20).

13. Upper refuse layers exhibited a higher degree of removal of inorganic leachate components than lower layers. This observation suggests that the leaching process is progressive through the refuse deposit. It is impossible to determine if the higher concentrations in the lower layers

were a result of filtration of the migrating component, or due to a lack of removal.

14. The organic component concentration as measured by percent ether extractable showed not only an increase with depth, but also showed quantities greater than originally extracted. This implies that in a landfill, a biological conversion of cellulose to a lower order organic substance occurs. This process would keep the COD of the leachate higher than would be expected from the initial chemical analysis. This observation is confirmed by the COD and final solid waste data.

15. Log plots of concentrations of specific leachate components against leachate removed per square foot of horizontal area indicate that once field capacity was reached, the rate of contaminant removal was greatly accelerated. The results also suggest that a specific removal rate can be established for a particular component by using such plots.

SHREDDED REFUSE STUDY

From the results of this study certain conclusions and recommendations about the operation of landfills containing shredded refuse can be made:

16. Milling of refuse will increase the field capacity and the elapsed time before the first leachate appearance will occur.

17. Milling of refuse to an effective diameter (D_{50}) of 3.5 to 13.5 mm. will significantly increase the rate of pollutant removal. Below this value, a decrease in rate of removal will occur. The maximum removal rate will occur at approximately $D_{50} = 10$ mm.

18. Milling of refuse will increase the in-place density, thereby increasing the pollutant removal per liter of leachate.

19. Landfills containing milled refuse, at an original moisture content lower than the field capacity of the refuse will have pockets of material which will be by-passed by the infiltrating water.

20. Milling of refuse significantly decreases the organic content as measured by the chemically decomposable organic content and the ether soluble percent of the refuse and increases the oxidizable iron.

21. Milling of refuse appears to have no significant effect on the permeability of the refuse.

22. Contact time of the percolating water has an effect on the concentration of the leachate. An increase in contact time produced either by an increase in field capacity or by a decrease in filtration rate will increase concentrations of pollutants in the leachate.

23. Landfills containing milled refuse will have significantly higher percentages of methane.

24. Landfills containing refuse at a moisture content less than field capacity and having low water infiltration rates will have higher temperatures initially.

FIELD FACILITY

25. Field temperature data indicated that field temperatures had a dampened phase response to atmospheric and ground temperatures.

26. Refuse temperatures nearest the boundaries corresponded very closely to boundary temperatures.

27. Initial temperatures were close to ambient, which indicated the lack of a high degree of biological activity. This initial temperature behavior pattern resulted from the relatively high refuse placement density, as well as the moderate atmospheric temperature at the time of refuse placement.

28. Overall temperatures at various locations within the landfill were higher than those at corresponding depths outside the fill and a few degrees above ambient soil temperatures.

29. Gas patterns were similar to those in the laboratory lysimeter. No carbon monoxide or hydrogen sulfide was detected.

30. In the granite gneiss derived soils of this site, there was little migration of any gas from the refuse into the surrounding soil. These results reflect primarily on the relative impervious nature of the residual soils and the ability of the gas to vent through the soil cover to the atmosphere.

31. Methane concentrations peaked at between thirty (30) and forty (40) percent. These concentrations compared favorably with those obtained in the lysimeter. This behavior

pattern clearly indicates that ambient temperature conditions, rate of moisture buildup to field capacity, and initial refuse density have a marked effect on the rate of decomposition, hence the rate of methane penetration.

32. The time of the first significant increase in contaminants in the soil underlying the landfill coincided with the moisture content of the refuse reaching field capacity. The correlation between system field capacity and first generation of significant quantities of leachate was excellent.

33. The concentrations of total dissolved solids decreased with increasing depth into the soil beneath the landfill. This observation indicates the ability of the soil to renovate the leachate. (It should be noted that the field test was not continued until complete leaching of the soluble contaminants was attained. Hence, final contaminant concentration patterns had not been observed.)

34. Wells in the ground water showed that any contaminant reaching the ground water table tended to move down gradient (horizontally). The zone of contamination was limited to a narrow band at the top of the ground water. The thickness of the contaminated layer will depend on the ground water velocity as well as the soil's vertical permeability and related physical factors at a specific site.

35. The contaminated zone in the ground water showed compositions similar to those found in the lysimeter leachate but greatly attenuated.

a) pH - Ranged between 5.0 and 8.0 with a mean of about 6.0.

b) COD - Maximum rise was to 2700 mg/l. The maximum occurred during the period when the refuse was first brought to field capacity. Generally, concentrations did not exceed 200 mg/l to 300 mg/l.

c) Iron - Maximum iron concentration reached 700 mg/l to 800 mg/l. The peak occurred during the period when the refuse was brought to field capacity.

The remainder of the contaminants had patterns similar to those described for pH, COD and iron. In general, the concentrations found in the field study were lower than those found in the lysimeter studies. Also, maximum peaks developed at the time when the entire landfill was borught to field capacity. This was accomplished in the field over a short time period by the addition of a large quantity of water.

ANALYTICAL STUDY OF LEACHATE MOVEMENT

36. Three mechanisms of mass transport were evaluated and found to have the following effects on the migration of leachate pollutants away from solid waste disposal site and into the ground water system:

(a) Convective dispersion due to microscopic velocity variations within the soil voids had the greatest effect in carrying leachate pollutants from the solid waste disposal site in the direction resulting from ground water flow and leachate infiltration.

(b) Chemical reaction, in its adsorptive sense, was responsible for retarding the migration of pollutants away from the solid waste disposal site in all directions. This effect was most significant in media containing active materials such as clay minerals.

(c) Molecular diffusion due to each leachate pollutant concentration gradient in the ground water had the least effect on the migration of leachate pollutants in the direction of the main ground water flow, but it had a noticeable effect on the lateral and normal diffusion of leachate pollutants from the solid waste disposal site.

37. Operational methods were used to develop closed form solutions for one-dimensional models of leachate pollutant migration in unconfined ground water systems. Although simplified theoretical models have restricted validity in field studies, a mathematical model of one-dimensional simultaneous diffusion and convective dispersion proved adequate for determining the effective diffusion coefficients. Because this model did not include a chemical reaction term, the theoretical breakthrough curves for soils containing organics and clay minerals showed lower correlation with the experimental results than did those for soils with low exchange capacity.

38. Good correlation was achieved between average field concentrations and theoretical pollutant profiles. Field concentrations were expressed in a non-dimensional ratio of total dissolved solids (TDS) measured at each observation well to the TDS at a reference source located beneath the center of the waste disposal site at the ground water table interface. Theoretical concentrations were determined by computer solution of a two-dimensional model of simultaneous

diffusion, convective-dispersion and chemical reaction. The model was expressed in the form of second order partial differential equation for both the horzontal and vertical domains. A convergent explicit difference equation was solved for appropriate boundary conditions and hydrogeologic parameters. Patterns of leachate pollutant migration were determined and represented graphically for both vertical and horizontal domains.

39. The pattern of ground water pollution was shown to be divided into three stages: a buildup stage, a steady-state stage, and a recovery stage. In the first two stages, leachate discharge from the waste disposal site was constant and continuous. The results showed that leachate pollutant concentration levels decreased with increasing distance from the source. The leachate pollutant concentrations in the two stages were always located at the disposal site downgradient boundary.

The third stage was started after stopping the leachate migration for a period of time. Recovery from leachate pollutants was pronounced directly beneath the disposal site soon after termination of the leachate source. The third stage is characterized by an inversion in concentration profiles and by a shift in the peak concentration away from the center of the source in the direction of ground water flow. Inversion phenomena provided a basis for explaining field experimental data that showed that some observation wells located close to the site had lower leachate pollutant concentration levels than wells at farther distances downgradient.

Inversions in the vertical domain were noticed in all three stages. They occurred because of the divergence of flow lines of infiltration leachate as it moves into the ground water system. The inversions were found at greater depths at successively greater distances from the leachate source.

40. The ground water velocity vector was found to be the major controlling parameter in this study. It controlled both the convective dispersion and the magnitude of the effective-diffusion coefficients. When the ratio of ground water flow velocity to leachate infiltration velocity was increased, leachate pollutants travelled greater distances down-gradient, but remained at shallower depths in the ground water. In addition, the rate of recovery of ground water from leachate pollution after stopping the sources occurred more rapidly with increasing ratio. This ratio could be used as a criterion for solid waste disposal site selection along with climatic and other hydrologic characteristics and the ground water use. By control of leachate

infiltration rates and local ground water velocities, leachate pollutants could be confined to the site's immediate vicinity or confined to the top layer of the ground water system.

41. The geologic materials which form the subsurface soils is a significant factor that influences the patterns of ground water pollution by leachate from solid waste disposal sites. The selection of sites in geologic formations containing active clay minerals could be significant in reducing the concentration of leachate pollutants in the ground water system. Reduction of leachate pollutant concentrations due to the presence of such clays is due to the simultaneous adsorption and chemical reaction of the pollutants on their surfaces. Also, existence of clay minerals in the layers below a solid waste disposal site reduces considerably the amount of leachate and its infiltration velocity. This would have the effect of reducing the leachate pollutant concentration level beneath the site and down ground water gradient from it.

GENERAL

42. The use of a laboratory sanitary landfill lysimeter to generate field behavior patterns is valid if the two systems are similar in physical and geometric characteristics.

43. The soils derived from the parent granite gneiss which underlies the test site can reduce leachate contaminant concentrations. However, the test site study was not carried to a point which would permit conclusions as to long term renovation effects.

44. Infiltration water control is essential to keeping leachate contamination from migrating too rapidly through the underlying soil.

45. Leachate which reaches ground water will concentrate in a relatively narrow zone near the surface. The resulting mix will move down ground water gradient (horizontally).

46. Proper surface grading, compaction and refuse handling procedures should keep leachate generation within limits which are dictated by site conditions.

47. A semi-log linear relationship exists between contaminant concentrations and quantity of leachate after field capacity is attained. The existence of this relationship permits quantitative determination of the landfill life. In addition, predictives of landfill potential behavior

patterns can be made to establish the generation rates at levels compatible with environmental conditions.

48. Gas measurements are important enough to be an integral part of any landfill operation. However, a careful evaluation of the gas monitoring system is essential to insure significant data being obtained.

SECTION 3

EXPERIMENTAL FACILITIES

The experimental facilities were used to provide a complete picture of the behavior of a sanitary landfill (as currently defined) under simulated and natural environmental conditions. The laboratory lysimeter functioned as a leachate and gas generator under controlled environmental conditions, while the field facility was operated under natural environmental conditions. The mini-lysimeters were used to evaluate ground refuse behavior parameters including their hydraulic properties and the quality and quantity of their leachate.

LABORATORY SANITARY LANDFILL LYSIMETER

Several designs for the laboratory lysimeter were evaluated during the initial stages of the project. The final design, which is presented herein, was the result of that effort. The lysimeter simulated the center of a sanitary landfill with an 8-foot-thick (2.44 m.) (at time of placement) refuse layer covered with a 2-foot (.61 m.) soil layer. These dimensions were chosen since they represented recommended practice(1,2). A major design criteria was that the environmental conditions within the lysimeter represent climate conditions common to southeastern Pennsylvania for a sanitary landfill located above micaceous granite gneiss bedrock in soils derived therefrom. Another major design criteria was the requirement that the laboratory landfill data be correlated with the field facility data.

Design Criteria

To simulate an in situ sanitary landfill, several site and physical conditions were incorporated in the design of the lysimeter and the preparation of the refuse. These conditions were:

1. The simulation of the center portion of a large sanitary landfill. Usually, a landfill covers a large areal extent relative to its thickness; therefore, transverse heat losses would be minimal in comparison to heat losses at its atmospheric and soil contact boundaries.

2. The simulation of atmospheric boundary conditions for southeastern Pennsylvania. Temperature levels and added water were equivalent to the average monthly atmospheric conditions for the locality.

3. The simulation of refuse-subsurface soil contact boundary temperatures at the same depth for southeastern Pennsylvania.

4. The lysimeter size was such as to insure the validity of collected data.

5. The size of the refuse components was such as to insure validation of any data collected.

6. The composition of the refuse represented a "typical" sanitary landfill.

Tank Characteristics

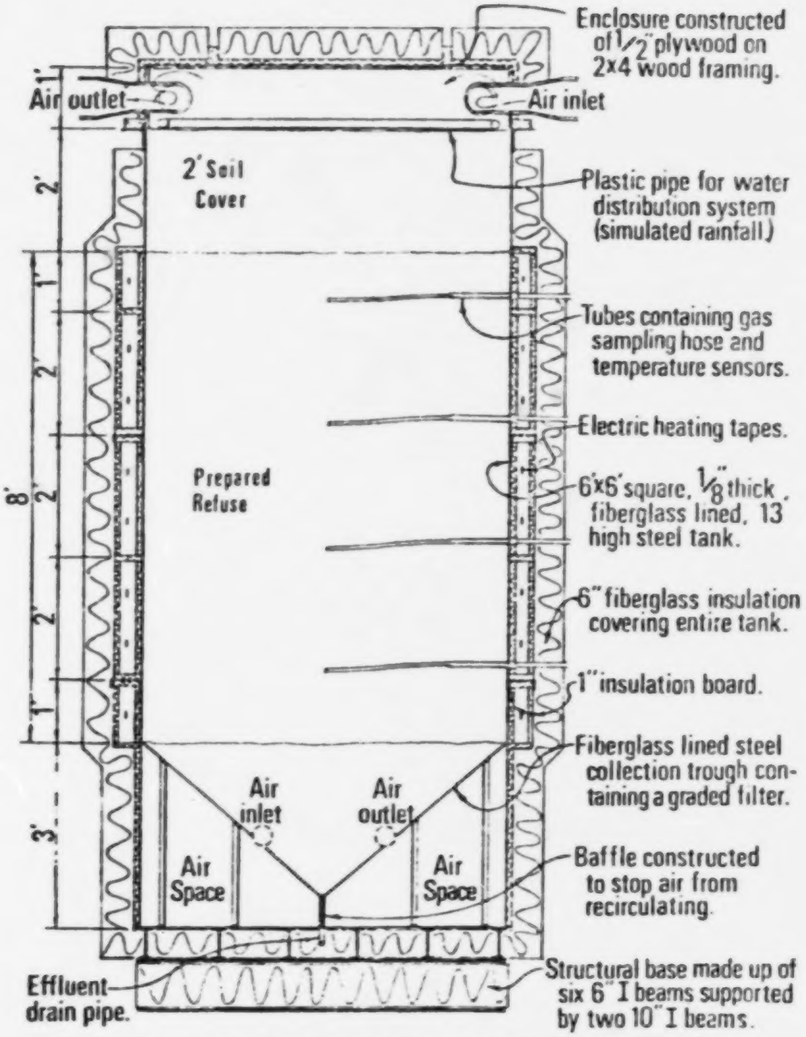
The lysimeter (Fig. 1) was constructed of 1/4-inch (6.35 mm.) low carbon steel plate. Interior walls were covered with 1/8-inch (3.175 mm.) thick fiberglass to protect the steel against corrosion due to the products of decomposition. The tank was thirteen feet (3.96 m.) high with a six-foot (1.83 m. square cross-section and was supported by six 6I12 steel beams equally spaced along its bottom. These beams, in turn, were supported by two 10135 steel beams which rested on the laboratory floor.

Leachate collection was facilitated by using an inverted pyramid-shaped trough (Fig. 2) which was located in the bottom of the tank and was constructed of low carbon steel covered with fiberglass. The side slopes of the trough were 1 on 1, and positioned at its apex was a 1/4-inch (6.35 mm.) stainless steel pipe for leachate removal. The interior of the trough was filled with Ottawa sand and glass spheres sized and arranged as shown in Figure 3. The sizes of the sand and spheres were selected to permit free passage of leachate. The total height of the trough was three feet (.91 m.), which reduced the interior tank height to ten feet (3.05 m.)

Environmental System

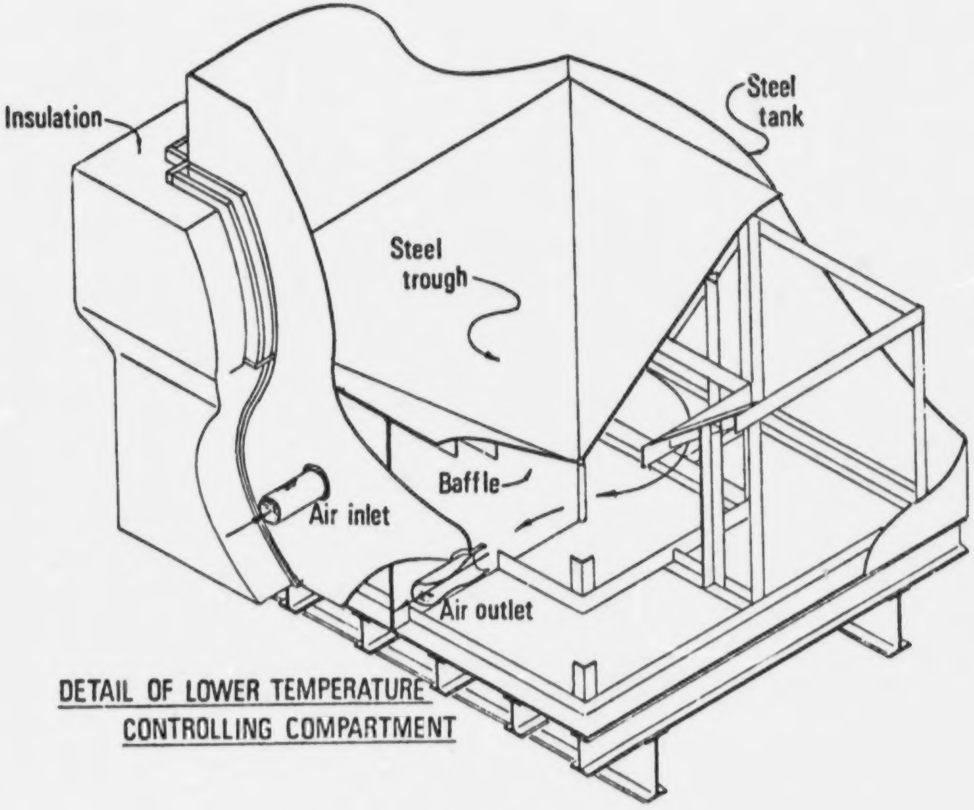
Bottom Air Temperature Control - The air space beneath the trough was maintained at a temperature of 57.2°F. This temperature was equivalent to the average yearly soil temperature at a depth of ten feet below the ground surface in southeastern Pennsylvania. A schematic of the cooling system is shown in Figure 4, section B-B. A section through the air space is shown in Figure 1.

Top Air Temperature Control - Air temperature above the landfill was changed monthly to conform with the average


Enclosure constructed of 1/2" plywood on 2x4 wood framing.
Air outlet
Air inlet
1'
2'
2' Soil Cover
Plastic pipe for water distribution system (simulated rainfall)
1'
Tubes containing gas sampling hose and temperature sensors.
2'
Electric heating tapes.
8'
2'
Prepared Refuse
6'x6' square, 1/8" thick, fiberglass lined, 13' high steel tank.
2'
6" fiberglass insulation covering entire tank.
1'
1" insulation board.
Fiberglass lined steel collection trough containing a graded filter.
3'
Air inlet
Air outlet
Air Space
Air Space
Baffle constructed to stop air from recirculating.
Effluent drain pipe.
Structural base made up of six 6" I beams supported by two 10" I beams.

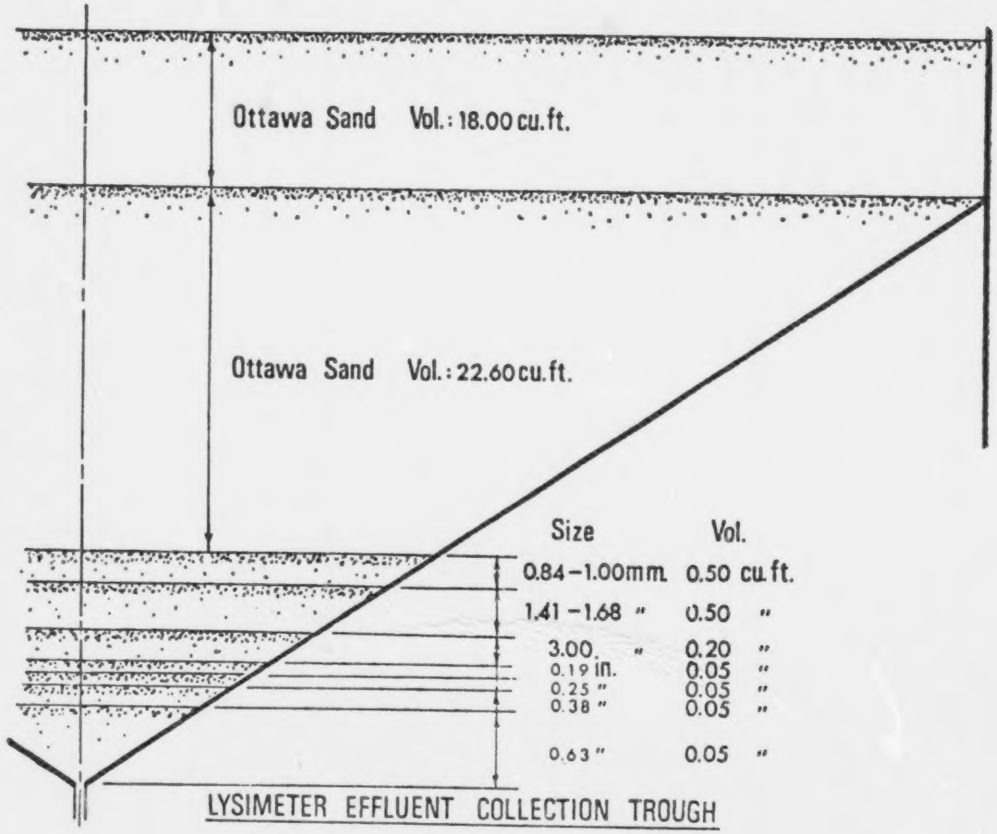
LYSIMETER CROSS SECTION – SIMULATED SANITARY LANDFILL

FIGURE 1



DETAIL OF LOWER TEMPERATURE CONTROLLING COMPARTMENT

FIGURE 2



LYSIMETER EFFLUENT COLLECTION TROUGH

FIGURE 3

monthly air temperatures in southeastern Pennsylvania. The average monthly air temperatures are listed in Table 1. Two systems were used to control this temperature.

The first system consisted of a controlled temperature air sweep which passed directly over the free surface of the cover soil. This system is shown in schematic in Figure 4, section A-A in the cross-section through the tank (Fig. 1). Early in the operation of the lysimeter, it was found that the air sweep across the soil introduced a small (a difference of less than one inch of water) positive pressure in the voids of the refuse. While the pressure presented no serious functional problem to the system, it was believed that it might affect gas movement within and out of the refuse. To eliminate the problem of positive air pressure, a system using cooling water circulating through 300 feet (91.44 m.) of 1/2 inch (12.7 mm.) Tygon tubing was developed. This system is shown in cross-section in Figure 5 and in schematic in Figure 6. Cooling water was pumped through the tubing at the rate of 1-1/2 gallons (5.68 l.) per minute and its temperature was controlled by an immersible cooling coil placed in a 55-gallon (208 l.) tank. It was possible to place this system directly on the top of the free soil surface due to refuse settlement (see section on compaction). This system and the original air system which was separated from the soil surface by a sealed steel plate interacted effectively in maintaining air temperatures above the soil surface.

Water Application System - Distilled water was added to the top of the soil cover, when needed, on a weekly basis. The water added represented the excess of precipitation over evapotranspiration for southeastern Pennsylvania. The quantities applied are given in Table 1. The water was distributed over the soil surface by means of 1-1/4 inch (31.75 mm.) rigid plastic pipe with 1/16 inch (1.59 mm.) diameter holes drilled in the top. The pipe system was gravity fed from outside the tank under a head of three feet. Using this system, the water "rained" lightly on the soil surface.

Insulation

Minimization of heat exchange through the lysimeter's vertical walls was most essential to its use as a simulator of the center of the landfill. To control heat exchange, the vertical walls of the lysimeter were completely insulated (Fig. 1). Two inches (50.8 mm.) of urethane insulation board, six inches (152.4 mm.) of fiberglass insulation, stagnant air pockets and heating tapes were used.

Heat Flow Into The Lysimeter - Movement of heat into the lysimeter, when internal temperatures were less than laboratory temperatures, was minimized by the combination of urethane

TABLE 1

Environmental Data for Southeastern Pennsylvania

Average Monthly Air Temperatures

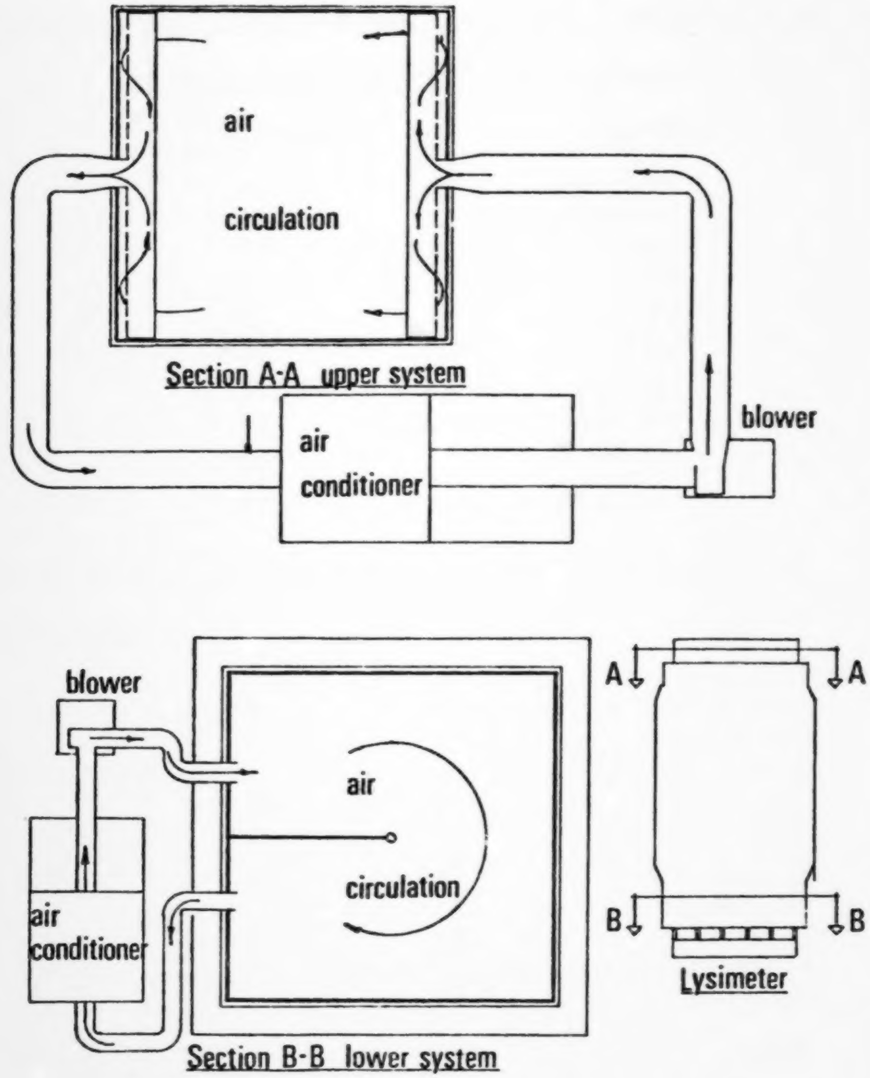
Month	Temperature $^{\circ}F$
January	33.4
February	33.8
March	41.3
April	52.1
May	62.7
June	71.4
July	76.0
August	74.3
September	67.6
October	56.6
November	45.1
December	35.1

Average Monthly Water Available for Infiltration

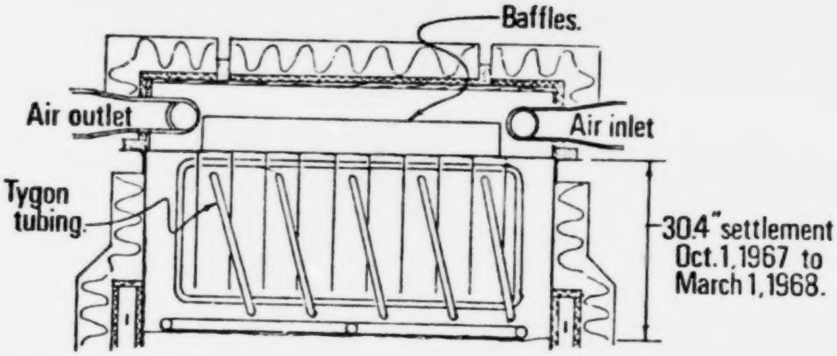
Month	P-ET (inches)*	Gallons/month**
January	3.40	76.3
February	2.95	66.2
March	3.40	76.3
April	1.66	37.3
May	.18	4.0
June	-1.18	0.0
July	-1.85	0.0
August	.28	6.3
September	.21	4.7
October	.89	20.0
November	2.78	62.4
December	3.03	68.0
Total	-	421.5 (18.78 inches)

*Precipitation minus Evapotranspiration

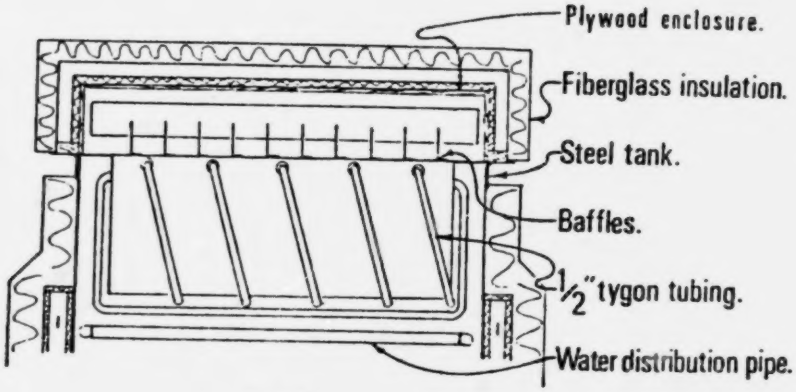
**Gallons per month on a 36 square foot area. Water is added weekly.



DETAILS OF AIR CIRCULATION SYSTEM
FIGURE 4

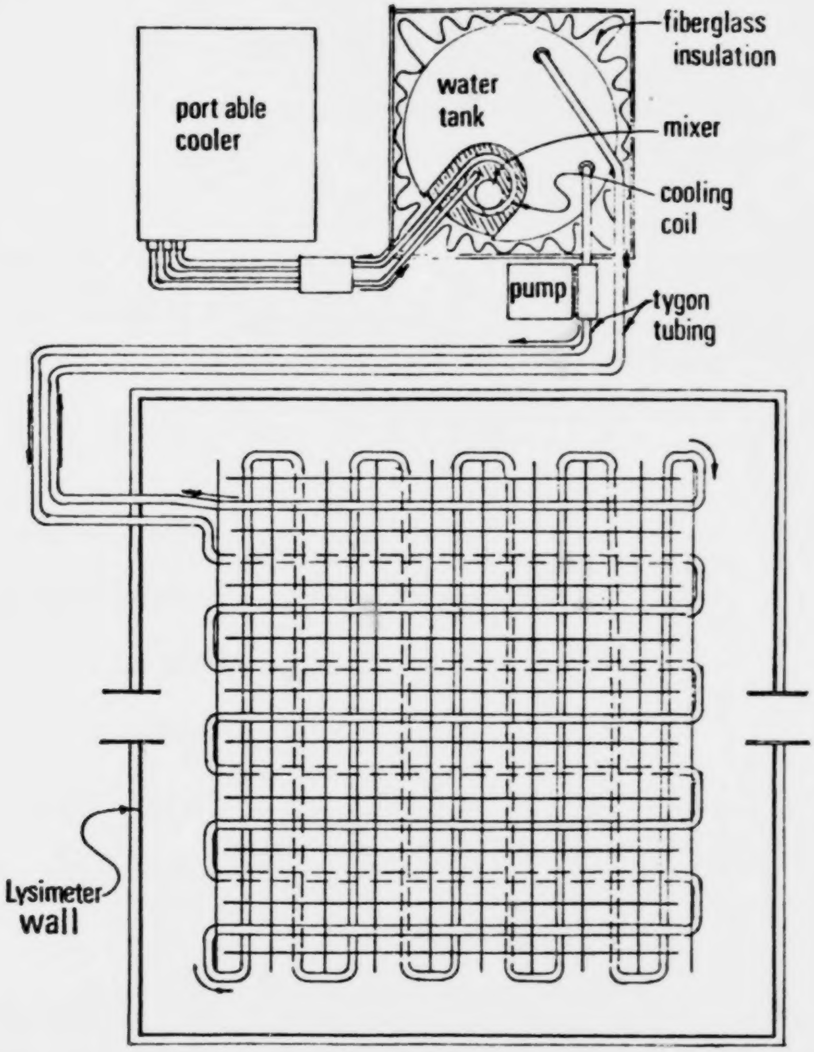


FRONT



SIDE

LYSIMETER COOLING SYSTEM (MODIFIED)
to simulate environmental temperature.
FIGURE 5



SCHEMATIC - WATER COOLING SYSTEM

FIGURE 6

insulation board, fiberglass insulation and stagnant air pockets.

Heat Flow Out Of The Lysimeter - Flow of heat out of the lysimeter was controlled by the same insulation system mentioned in the previous section, and heating tapes located in the stagnant air pockets (Fig. 7). The heating tapes were energized by thermistor-activated controllers which supplied power. These bands of "active" insulation covered one-foot segments at the top and bottom of the refuse zone and three two-foot intermediate zones. Each zone had its own controller and functioned independently of the others. The use of zoning permitted control of heat outflow at each level. Local control was necessary when temperatures inside the lysimeter were not constant vertically.

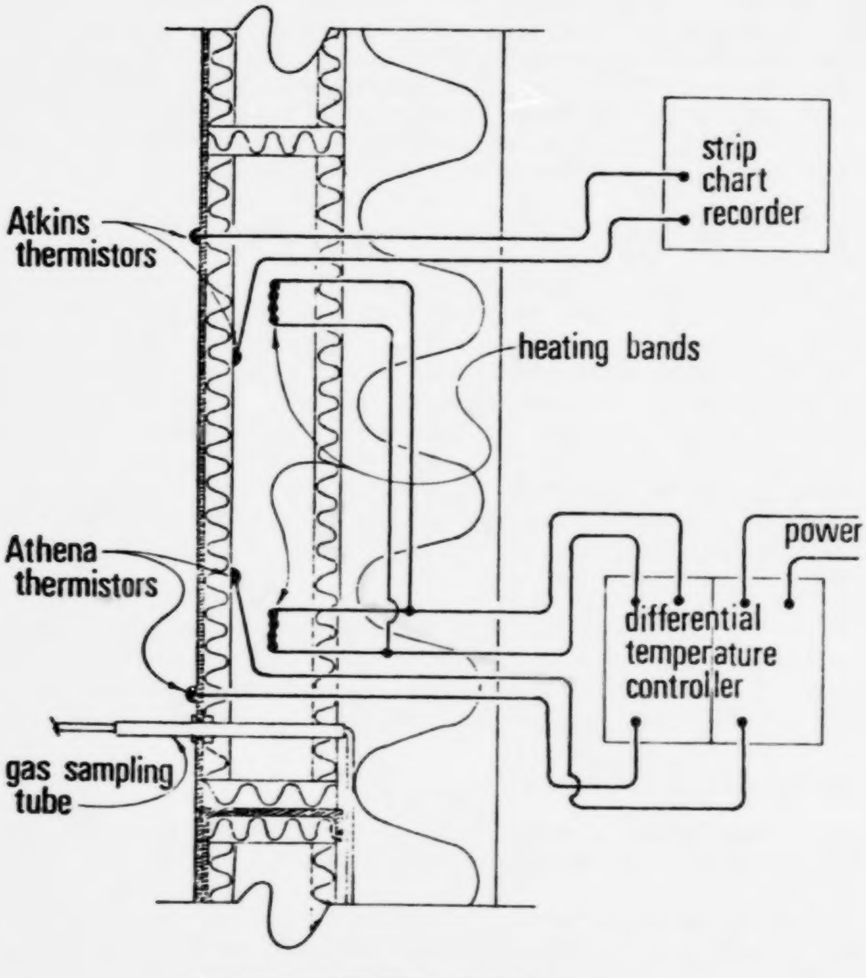
When the laboratory temperatures were higher than the interior temperatures, at any level, the tapes did not heat the stagnant air pockets. However, when the temperature at a particular level in the lysimeter was greater than the laboratory temperatures by at least 1^oF, the corresponding tape was turned on by the controller. Power to heat the tapes was supplied in an amount proportional to the temperature difference, but at a rate so as to minimize overshooting of the desired temperature. The tapes were turned on until the difference between the internal temperature, at any level, and the corresponding stagnant air space temperature was less than 1^oF. When a difference of 1^oF or less was reached, the tapes were inactivated.

In addition to the controlling thermistors, an auxiliary set of thermistors was used to monitor the behavior of the heating tapes. Location of a typical set of thermistors and a schematic of the controller are shown in Figure 7.

Instrumentation and Sampling

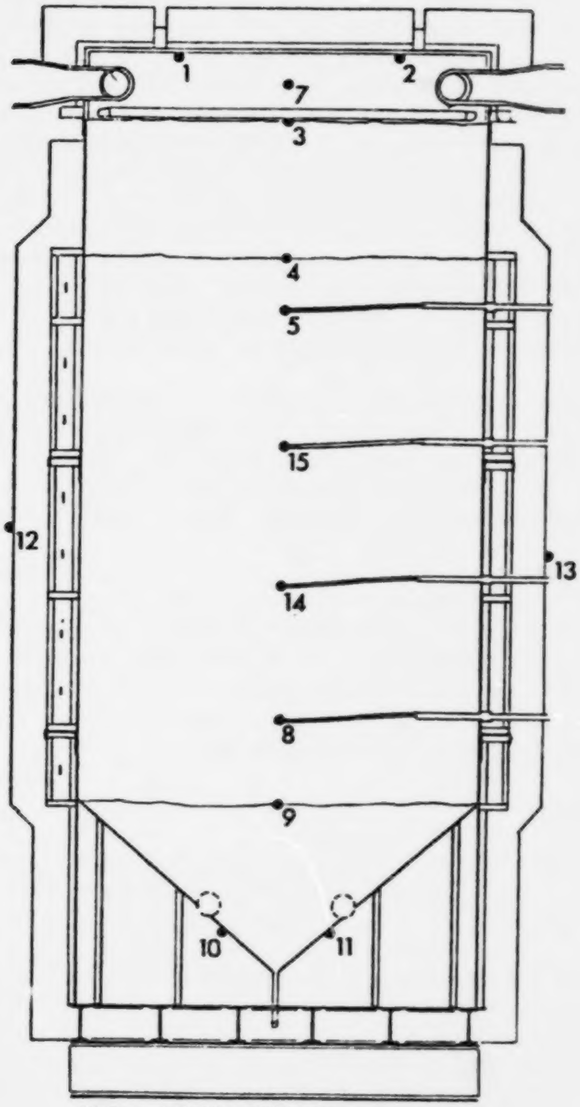
Three major parameters were monitored: temperatures, gases, and quantity and composition of the leachate.

Temperatures - An automatic scanning-printing system using thermistors and a digital thermometer was used to monitor temperatures. Temperatures were measured at seven locations inside the lysimeter and at two exterior locations. Thermistor locations, at time of fill placement, are shown in Figure 8. The thermistors monitored temperatures in the air space above the soil cover, at the air-soil cover interface, at the soil cover-refuse interface, at 1, 3, 5 and 7 feet below the top of the refuse, at the refuse-Ottawa sand interface, in the bottom air sweep and at two locations outside the tank.



HEATING CONTROL SYSTEM

FIGURE 7



Y.S.I. THERMISTOR LOCATION
FIGURE 8

Initially, temperatures were recorded every hour, but the system was changed over to four-hour record time after the temperature changes ceased being highly transient.

Gas Samples - Gases were sampled at five different locations in the tank. The sampling positions, which are shown in Figure 1, were the sampling ports on the side of the tank at depth of 3 (.91 m.) 5 (1.52 m.), 7 (2.13 m.) and 9 (2.74 m.) feet below the top soil surface (as initially placed) and in the air space above the cover soil surface, but below the steel coverplate. Side samples were taken through 1/2-inch (12.7 mm.) diameter Tygon tubing which ran from the center of the lysimeter through ports on the side of the tank. To sample the air above the soil cover, a 1/8-inch (3.175 mm.) diameter tube was temporarily disconnected from a wet gas meter (the wet gas meter was used to maintain atmospheric pressure). After sampling, the air space was purged to maintain "atmospheric" conditions.

Gas samples were taken three times a week and analyzed for the gases listed in Table 2. The sampling techniques and analytical procedures are described in "Pollution of Subsurface Water by Sanitary Landfills", Volume 1, U. S. Environmental Protection Agency, Washington, D.C., 1971.

Leachate - Leachate, when available, was collected in the bottom trough and removed through the drain once a week. The analyses performed on the leachate are listed in Table 2. Analytical procedures are described in "Pollution of Subsurface Water by Sanitary Landfills", Volume 1, U.S. Environmental Protection Agency, Washington, D. C., 1971. Leachate quantity was also measured.

Refuse Placement

Materials - The refuse composition was patterned after the analysis of Kaiser(3) and at placement had the composition listed in Table 3.

The refuse was sized so as to minimize size influence. Cardboard pieces were not larger than one foot square. Small pieces of metal and unrolled cans were used to eliminate compaction and placement problems due to arching and large voids. Other paper products such as glass and plastics were also sized to prevent their having an unrealistic influence on lysimeter functioning.

Compaction - A procedure was developed for external compaction, since it was not possible to compact the refuse within the lysimeter. The general scheme consisted of

TABLE 2

List of Liquid and Gas Sample Analyses

Liquid

Chemical oxygen demand
Chloride
Copper
Dissolved oxygen
Hardness
Iron
Nickel
Nitrate
Nitrogen (ammonia, organic)
pH
Phosphate
Sodium
Sulfate
Suspended solids
Total residue (total dissolved solids)
Zinc

Gas

Carbon dioxide
Carbon monoxide
Hydrogen sulfide
Methane (total hydrocarbons)
Nitrogen
Oxygen

TABLE 3
Refuse Composition - Laboratory Lysimeter

PERCENT COMPOSITION OF REFUSE (4)

Percent	
23.38	Corrugated paper boxes
9.40	Newspapers
6.80	Magazine paper
5.57	Brown paper
2.75	Mail
2.06	Paper food cartons
1.98	Tissue paper
0.76	Plastic coated paper
0.76	Wax cartons
2.29	Vegetable food wastes
1.53	Citrus rinds and seeds
2.29	Meat scraps, cooked
2.29	Fried fats
2.29	Wood
1.53	Flower garden plants
1.53	Lawn grass, green
1.53	Evergreens
0.76	Plastics
0.76	Rags
0.38	Leather goods
0.38	Rubber composition
0.76	Paints and oils
0.76	Vacuum cleaner catch
1.53	Dirt
6.86	Metals
7.73	Glass, ceramics, ash
9.05	Adjusted moisture
100.00	

Component	Gms. Pollutant/gm. dry refuse wt.
Crude fiber	38.3%
Moisture content	18.2%
Ash	20.2%
Free carbon	0.57%
Nitrogen	
a) free ammonia	0.02 mg/gram
b) organic	0.35 " "
Water solubles:	
a) sodium	1.95 " "
b) chloride	2.00 " "
c) sulfate	2.19 " "
C.O.D.	25.25 " "
Phosphate	0.29 " "
Hardness	10.12 mg/$CaCO_3$/gm.
Major Metals:	
Aluminum, Iron, Silicon	>5.00% (by spectrographic analysis)
Minor Metals:	
Calcium, Magnesium, Potassium	1.0-5.0% (by spectrographic analysis**)

**Of non-volatile portion

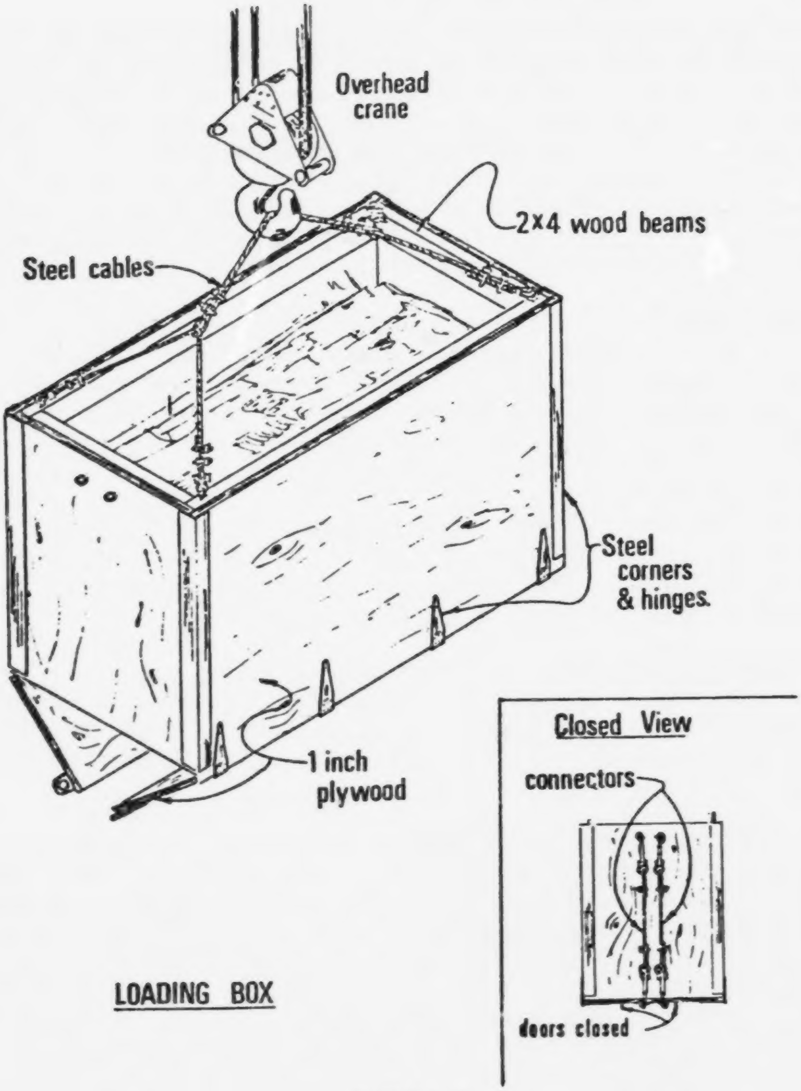
filling (with a mixture of prepared refuse) six foot (1.83 m.) by three foot (.91 m.) by two foot (.61 m.) wooden boxes which had a trap door bottom (Fig. 9). The refuse components were premixed by hand prior to placement. The refuse was the compressed in the box in the steel frame, shown in Figure 10, by using a steel coverplate loaded by the hydraulic jack. The frame was designed to facilitate insertion and removal of the refuse boxes.

The refuse was compacted until the original height of two feet had decreased to one foot (.30 m.) for a compaction ratio of 2:1. The 2:1 compaction ratio occurred when the unit pressure on the refuse was approximately six pounds per square inch. As discussed elsewhere(4), use of the 2:1 compaction ratio criteria did not prove entirely satisfactory. Upon release of the compaction pressure, a rebound of approximately two inches occurred. At the compaction ratio of 2:1, a dry density at placement of approximately 327 lbs/yd^3 (194 kgs/m^3) was obtained.

After compaction in the frame, each load was placed in the tank by means of an overhead crane. Eight one-foot (.30 m.) layers of compacted material were required to fill the tank to the desired refuse height. Each layer required two loads for a total of sixteen compactions. To place the refuse, the loading box was first positioned so that the bottom trap door rested on previously placed material. Then, the end straps (Fig. 10) were removed and the box raised to allow the doors to open. This procedure permitted the compaction material to be deposited with minimum distrubance. All voids and corners were hand filled to insure elimination of any large channels.

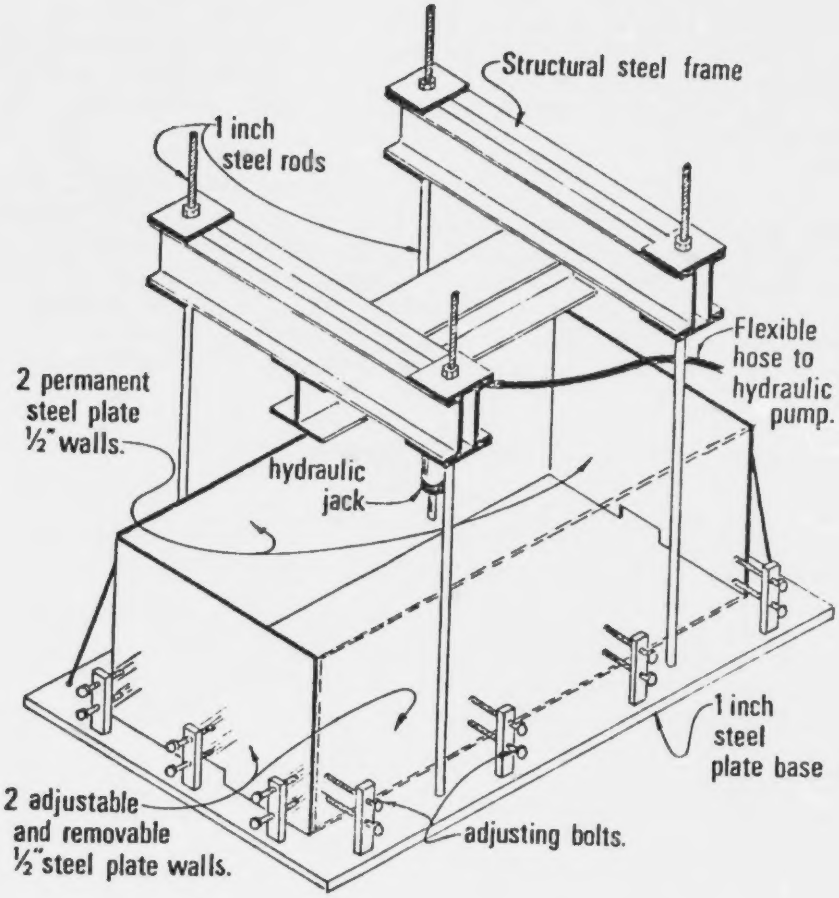
After placement, the refuse was covered with two feet of soil taken from the field site (described in the next section). The soil was hand tamped into position, and at placement, had a dry density of 110 lbs/ft^3 (1762.2 kgs/m^3) and a moisture content of 35.2% (dw).

The total weight of the soil cover resulted in approximately 1-1/2 lbs/in^2 of contact pressure on the refuse. The immediate settlement, 13.4 in. (34.0 cm.), resulted in a refuse depth of 8ft. (2.4 m.) and a dry density of 378 lbs/yd^3 (224.28 kgs/m^3).



LOADING BOX

FIGURE 9


Structural steel frame
1 inch steel rods
Flexible hose to hydraulic pump.
2 permanent steel plate ½" walls.
hydraulic jack
1 inch steel plate base
2 adjustable and removable ½" steel plate walls.
adjusting bolts.

REFUSE COMPACTION FRAME

FIGURE 10

FIELD SANITARY LANDFILL FACILITY

During the planning stages of this study, several existing landfills were evaluated for their potential use. The primary reason for acceptance of the site utilized was the fact that it was a new landfill, which could be studied from time of initial placement. Other factors which were weighed in the final determination were the quality of the proposed landfilling operation, the natural terrain of the site, the proximity to Drexel, and the site location relative to existing human habitation. Specific reasons for selection of this site, relative to ground water and site geology, are enumerated in the section of location.

Location

The test site was a portion of the southeastern Chester County Sanitary Landfill located in Kennett Township, Chester County, Pennsylvania at the intersection of North Walnut Street and Route #1 Bypass (Fig. 11). It was immediately north of Kennett Square, Pennsylvania and was bordered on the west by the east branch of the Red Clay Creek.

The test site was selected for the following reasons:

1. The site was underlain by metamorphic bedrock: the geologic materials were typical of a common formation which extends from Washington, D.C. to Boston, Massachusetts.

2. The test site was located in a new landfill: the use of a virgin site permitted the obtaining of background chemical and physical data for both soil and water, which did not reflect any landfill operation.

3. The test site was well above ground water: the soils and saprolite (weathered bedrock) were deep and well drained.

Climate Conditions

The field installation was located in the semi-humid northeastern part of the United States. Thirty-year monthly average precipitation and temperature data are given in Table 4.

Geology - Soils

Regional Geology - The southeastern Pennsylvania region is largely underlain by the Wissahickon schist formation (Lower Paleozoic Age), granite gneiss and gabbroic gneiss and gabbro (Precambrian Age). These metamorphic rocks under-

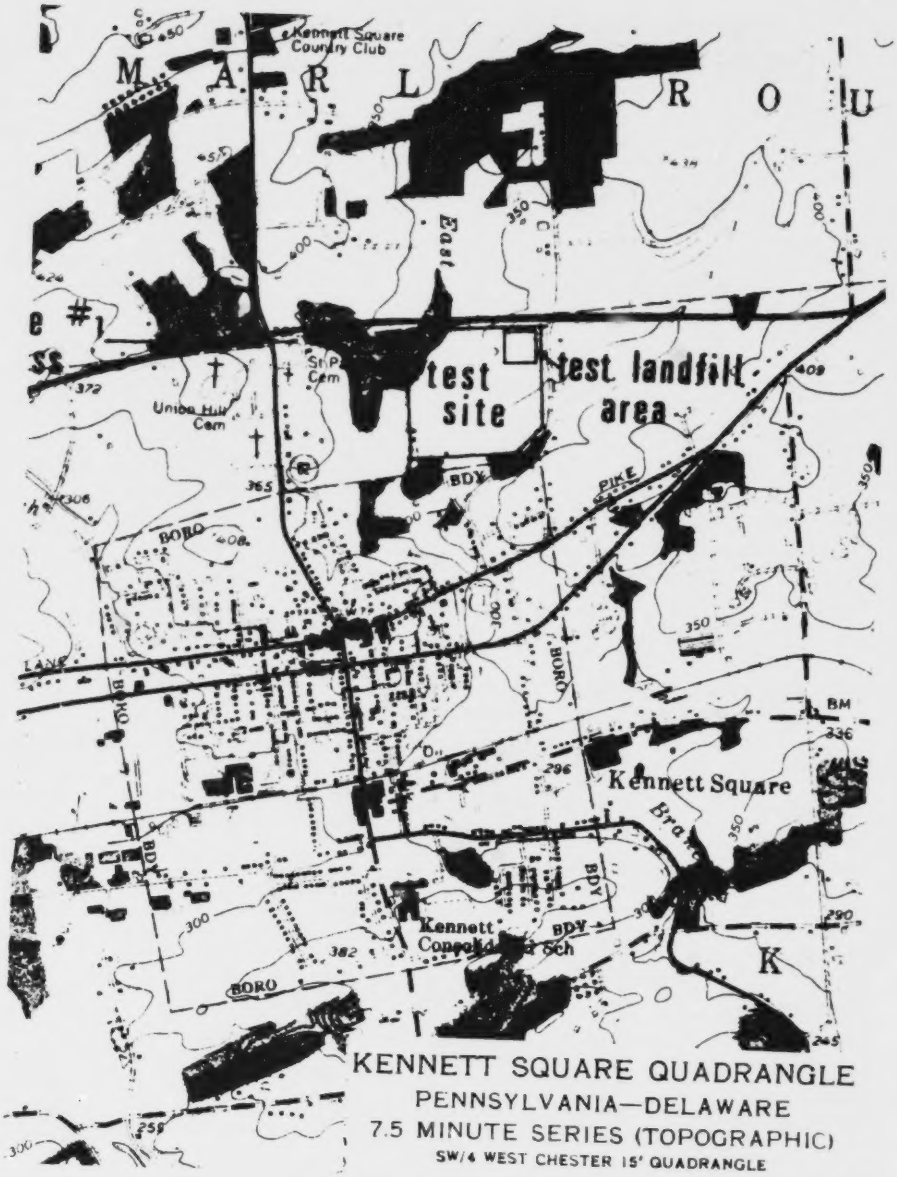

Kennett Square Country Club
M A R L
R O U
East
test site
test landfill area
Union Hill Cem
St. P. Cem
BDY
PIKE
BORO
LANE
Kennett Square
Kennett Consolidated Sch
BORO
K
KENNETT SQUARE QUADRANGLE
PENNSYLVANIA—DELAWARE
7.5 MINUTE SERIES (TOPOGRAPHIC)
SW/4 WEST CHESTER 15' QUADRANGLE

FIGURE 11

TABLE 4

Thirty Year Average Precipitation and Temperature Data for Wilmington, Delaware

Thirty Year Average Precipitation

Month	Inches
January	3.40
February	2.95
March	4.02
April	3.33
May	3.53
June	4.07
July	4.25
August	5.59
September	3.95
October	2.91
November	3.53
December	3.03
Total	44.56

Thirty Year Average Maximum and Minimum Temperatures

Month	Maximum	Minimum	Average
January	41.3	25.5	33.4
February	42.4	25.2	33.8
March	50.5	32.0	41.3
April	62.5	41.6	52.1
May	73.4	52.0	62.7
June	81.8	61.0	71.4
July	86.2	65.8	76.0
August	84.2	64.3	74.3
September	77.9	57.3	67.6
October	67.3	45.9	56.6
November	55.1	35.7	45.4
December	43.5	26.7	35.1
Annual	63.8	44.4	54.1

Source: Department of Commerce, Weather Bureau lie the metropolitan region from Washington, D.C. to Boston, Massachusetts. These rocks are extensively faulted and have similar hydrogeologic characteristics. Bedrock is usually deeply weathered and highly decomposed resulting in a thick saprolite zone. The most common soils that de-develop in material weathered from this rock type belong to the Glenville, Chester, Glenelg and Worsham series.

The Glenelg series consists of moderately deep, well-drained soils of uplands. The soils have moderate permeability and are better drained than the Glenville series. The Chester series consists of soils deep and well-drained with moderate to moderately rapid permeability.

The Glenville series consists of deep, moderately well-drained soils. They are on concave areas in the uplands and around the heads of streams, where the water table is high in the soil for long periods. Their permeability is moderately low.

The Worsham series consists of deep poorly drained soils of uplands. They have low permeability and are water-logged most of the time. They occur around seeps fed by springs at the heads of streams, along small streams, in slight depressions and along areas at the base of slopes.

Ground water is under water table conditions flowing from topographic highs to lows. The source of this ground water is rainfall that has infiltrated locally to recharge the ground water aquifers.

Site Geology - The site consists of a northeast-southwest drained topographic high with a range in elevation from 320 feet (97.54 m.) to 380 feet (115.82 m.) above mean sea level. The map location for this site is 11.6 inches (294.64 mm.) west and 3.75 inches (95.25 mm.) south of the northeast corner of the Kennett Square, Pennsylvania - Delaware 7-1/2 minute quadrangle. The portion of the quadrangle relevant to this study is shown in Figure 11.

Ten soil identification pits were dug during the initial site investigation. Soil in these pits varied from 35 inches (.89 m.) to 61 inches (1.55 m.) in depth overlying saprolite, a highly weathered bedrock. The general soil conditions consist of the Glenville and Worsham soils located below the 350 foot contour line and the Glenelg and Chester soil located above this elevation. The granite gneiss underlying the site is largely deeply weathered, micaceous, friable to compact, fine to medium bedded, has iron staining on joints and bedding planes, and is locally quartz-rich. Depth of bedrock is generally shallower on the crest of the topographic high.

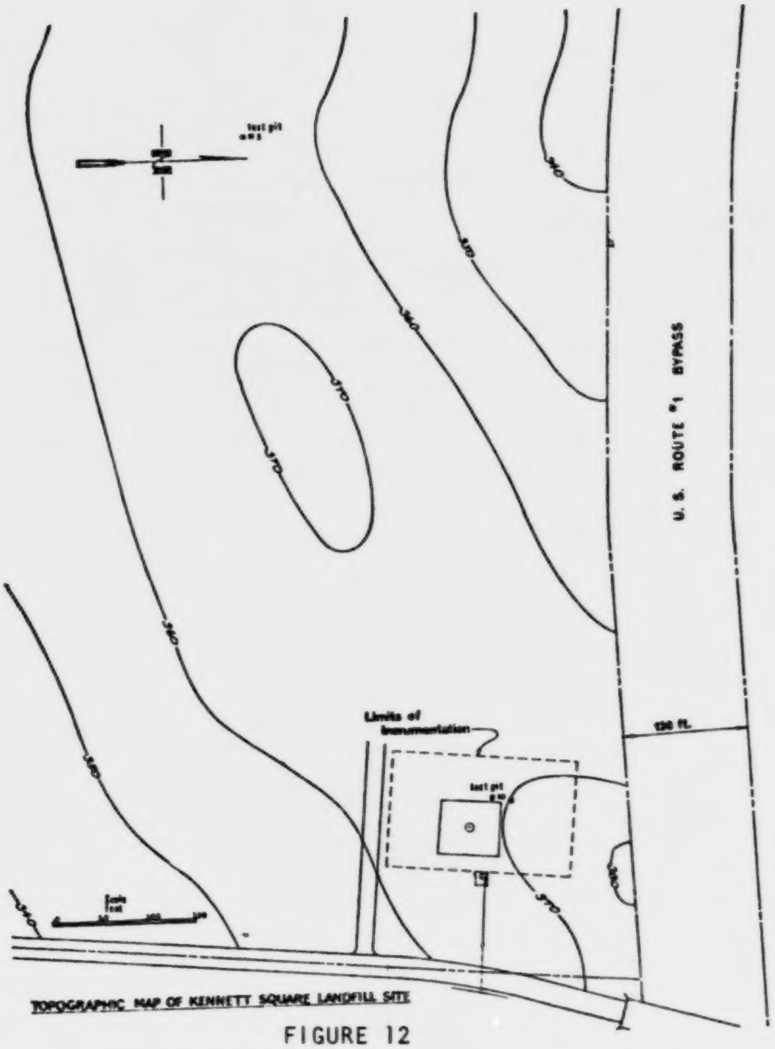
A detailed description of two of the soil identification pits is adequate for the site. The approximate locations of these soil identification pits are indicated in Figure 12. The descriptions for these pits are given in Tables 5 and 6.

The direction of ground water movement beneath most of the site is toward the southwest where it discharges into an unnamed tributary of the East Branch of the Red Clay Creek.

At the extreme northern edge of the site, ground water movement is toward the highway cut for U.S. Route #1 Bypass. Ground water movement at the western end of the site is toward the west to the East Branch Red Clay Creek, which flows in a southern direction. Two reservoirs for the Kennett Square water supply are present at the west end of the site between the stream and the landfill site. They are approximately 10 feet (3.05 m.) above the stream level and are hydrologically isolated from the ground water flow system. Southwestward drainage is present approximately 1/4 mile (402.25 m.) south of the site. The confluence of the unnamed tributary and East Branch Red Clay Creek is near the southwest corner of the site in the headwaters region of the creek.

There is one well, approximately 80 feet deep (24.4 m.), in the vicinity of the landfill. It is located 321 feet (97.8 m.) east of the test landfill at a private residence. At this distance and location, it does not have any influence on the direction of ground water movement at the test landfill.

Test Pit Geology - The location of the test landfill is shown in Figure 12. The predominant soil type is a strong brown silt loam which is blocky, friable when moist, non-sticky and non-plastic when dry. It is of the Chester series marginal with Glenelg series. The bulk density of this soil falls within the range of 1.19 to 1.59. The average moisture held at 40 mm. tension is approximately 25 percent by weight. The permeability of these soils varies between 1.84 and 30×10^{-4} cm/sec. Using an average density of 91.4 lbs/ft^3 (1464 kgs/m^3) for undisturbed sub-strata and an average cation exchange data for the "C" horizon for Chester and Glenelg soils, the exchange capacity has been calculated to be 4,440 milligram equivalents/ft^3 (.157 milligram equivalents/cm^3) of which 2,200 (.078) are hydrogen ions and the remainder metallic cations, mostly calcium and magnesium. This cation exchange capacity represents a considerable absorptive and renovating power. The extractable cations consist mainly of calcium.



TOPOGRAPHIC MAP OF KENNETT SQUARE LANDFILL SITE

FIGURE 12

TABLE 5

Test Pit No. 10

DEPTH (inches)	HORIZON	DESCRIPTION
0 - 13	AP	Dark-grayish brown silt loam, weak, fine and medium granular structure. Very friable. Non-stocky, non-plastic when wet, abrupt lower boundary. Range 10 inches to 15 inches.
13 - 20	B21	Strong (silt loam). Brown in color. Moderate medium - sub-angular blocky. Friable - non-sticky, non-plastic, granular wavy lower boundary. Thickness ranges from 5 inches to 9 inches.
20 - 25	B22	Yellowish brown loam, partial clay films, weak sub-angular blocky structure. Clear wavy lower boundary. Thickness ranges from 3 inches to 8 inches.
25 - 36	B3	Strong brown and yellowish brown loam, weak platy structure. Friable, non-sticky, non-plastic gradual wavy lower boundary. Thickness ranges from 10 inches to 16 inches.
36 - 60	C	Saprolite, very micaceous (biotite), dark gray/black, weathered to orange brown. Thin stringers of white micaceous deeply weathered feldspar. Gneissic bedding.
60 - 148		Deeply weathered, slightly macaceous saprolite. White, yellowish brown and manganese staining on bedding planes and joint surfaces. Saprolite is primarily a slightly macaceous feldspar with varying amounts of quartz. Clear quartz veins common. Weathered rock is incoherent to slightly coherent. Joints are closed. N60E - 315 feet.

TABLE 6

Test Pit No. 5

DEPTH (inches)	HORIZON	DESCRIPTION
0 - 9	AP	Dark grayish brown loam, very friable, non-sticky, non-plastic, abrupt smooth lower bound. Range 8 inches to 10 inches.
9 - 18	B21	Brown loam, very friable, weak sub-angular. Blocky structure, partial clay films, friable, non-stocky, non-plastic, 20 percent coarse fragments. Range ± 2 inches, 7 inches to 11 inches.
18 - 25	B22	Dark brown loam, friable, non-stocky, non-plastic, few clay films. Twenty percent coarse fragments lower bound. Abrupt, wavy. Range 5 inches to 9 inches, gradual wavy.
25 - 35	B3	Brown sandy loam, friable. Ten percent coarse fragment lower bound. Abrupt, wavy, non-stocky, non-plastic.
35 - 88	C	Light gray, yellow brown and brown saprolite. Sandy. Range 60 inches to 88 inches at rock.
35 - 44		Deeply weathered granite gneiss, slightly micaceous, white, orange grown staining on bedding plane. Friable, scattered quartz veins.
44 - 49		Deep brown, very micaceous gneiss, deeply weathered, friable to compact.
49 - Rock		Saprolite, brown micaceous to very micaceous. Friable to compact, deeply weathered, long bedding planes.
Bedrock - Hole Depth, 120 inches		Granite gneiss, slightly micaceous, white to light gray, weathered along joints, fine to medium bedded. Thin quartz veins, thin zones of deeply decomposed rock, no open joints or bedding planes. 53 degrees South - North 60 East.

Air rotary drill borings were made to determine subsurface conditions and to install the various sampling tubes. On the basis of three borings (Nos. 8, 10, 11; Fig. 13), in the immediate vicinity of the test landfill, the following geological conditions were found to exist: three feet of field silt loam soil overlying 33 feet (10.06 m.) to 37 feet (11.28 m.) of a soil micaceous gneiss bedrock.

Samples of the saprolite were taken in the base of the test pit. The typical saprolite, which comprises about 75 percent of the pit floor is micaceous with abundant feldspar and a moderate amount of quartz. Approximately 20 percent of the area is a predominantly quartz-rich saprolite, and approximately 5 percent of the area is an iron- and manganese-rich saprolite.

Ground water occurs at depths of 20 feet (6.1 m.) to 22 feet (6.71 m.) in the 11 borings around the test landfill. The direction of ground water movement is to the southwest with a gradient of approximately 1/2 foot (152.4 mm.) in 20 feet (6.1 m.) (Fig. 14). The test site is located so that ground water movement is away from the site and is not affected by adjacent landfilling operations. Water levels showed a slight rise from November 11, 1967 to March 11, 1968 of 0.3 feet (91.44 mm.) to 0.5 feet (152.4 mm.). Spring recharge took place between March 11, 1968 and May 10, 1968 as water levels rose approximately 1 foot (.305 m.) to 1.5 feet (.457 m.).

Site Plan

The general topography of the site and the parcel used for this study are shown in Figure 12. In general, the northeastern end of the site (the test landfill location), has a relatively gentle slope. Toward the northwestern end of the site, the ground surface falls sharply toward U.S. Route #1 Bypass. This change in topography is not considered significant because the test area is approximately 500 feet (152.4 m.) removed from the slope.

Details of the portion of the site instrumented for this study are shown in Figure 13. Preliminary instrumentation began in the summer of 1967. At that time, a 50 foot (15.24 m.) by 50 foot (15.24 m.) by 10 foot (3.05 m.) deep pit was excavated and instrumentation was initiated.

Upon completion of the filling operation (described later) in May of 1968, the ground surface of the test area was contoured so as to retain all precipitation on the 50 foot (15.24 m.) by 50 foot (15.24 m.) fill area and to prohibit area inundation by any external surface water.

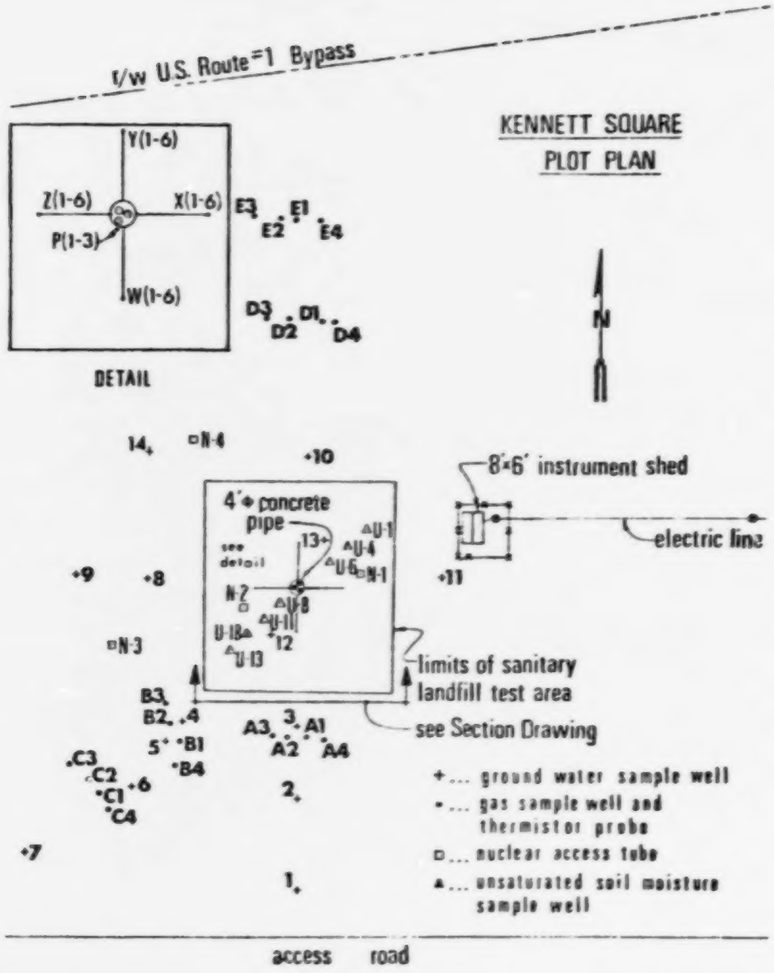

r/w U.S. Route #1 Bypass
KENNETT SQUARE
PLOT PLAN
Y(1-6)
Z(1-6)
X(1-6)
P(1-3)
W(1-6)
DETAIL
E3
E2
E1
E4
D3
D2
D1
D4
N
14
N-4
10
8'×6' instrument shed
electric line
4' ϕ concrete pipe
see detail
13
U-1
U-4
U-6
N-1
N-2
U-8
U-11
U-18
12
U-13
9
8
11
N-3
limits of sanitary landfill test area
see Section Drawing
B3
B2
4
5
B1
B4
A3
3
A1
A2
A4
C3
C2
C1
C4
6
2
7
1
+... ground water sample well
•... gas sample well and thermistor probe
□... nuclear access tube
▲... unsaturated soil moisture sample well
access road

FIGURE 13

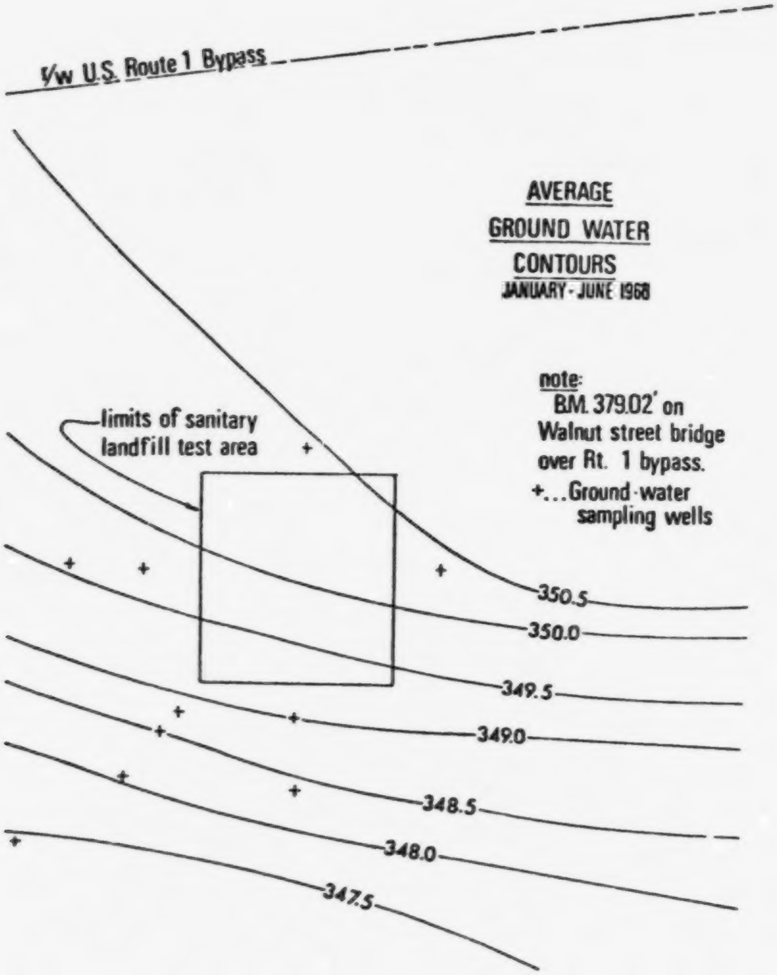

r/w U.S. Route 1 Bypass
AVERAGE GROUND WATER CONTOURS
JANUARY - JUNE 1968
note:
B.M. 379.02' on Walnut street bridge over Rt. 1 bypass.
+...Ground-water sampling wells
limits of sanitary landfill test area
350.5
350.0
349.5
349.0
348.5
348.0
347.5

FIGURE 14

Instrumentation

Basic instrumentation of the site was similar to that of the laboratory lysimeter. Instrumentation began in the Fall of 1967 after excavation of the test pit.

A four-foot diameter concrete pipe was located in the center of the test pit. This concrete pipe served as a hub from which all horizontal instrumentation extended into the test pit. The location of the pipe is shown in Figure 13, and a cross-section is shown in Figure 15. A cross-section through the entire fill area is shown in Figure 16.

Gas Samples - Gas sample tubes were located within the fill and at various locations in the in situ earth material above the water table. Locations were chosen so as to monitor gas and temperature changes both horizontally and vertically inside, outside and beneath the test landfill. Lateral sampling tubes extended from the center concrete pipe into the test landfill. Vertical sampling tubes extended from the ground surface to the various sampling depths. Tube locations are shown in Figure 13. Series A through E and P designate clusters of vertical gas tubes. Series W through Z designate the lateral gas tubes. Sampling depths are summarized in Table 7.

Figure 17 is a schematic of a gas sampling tube and thermistor well. The wells were placed using a four inch rotary drill. Each hole was predrilled and then instrumented using the following sequence:

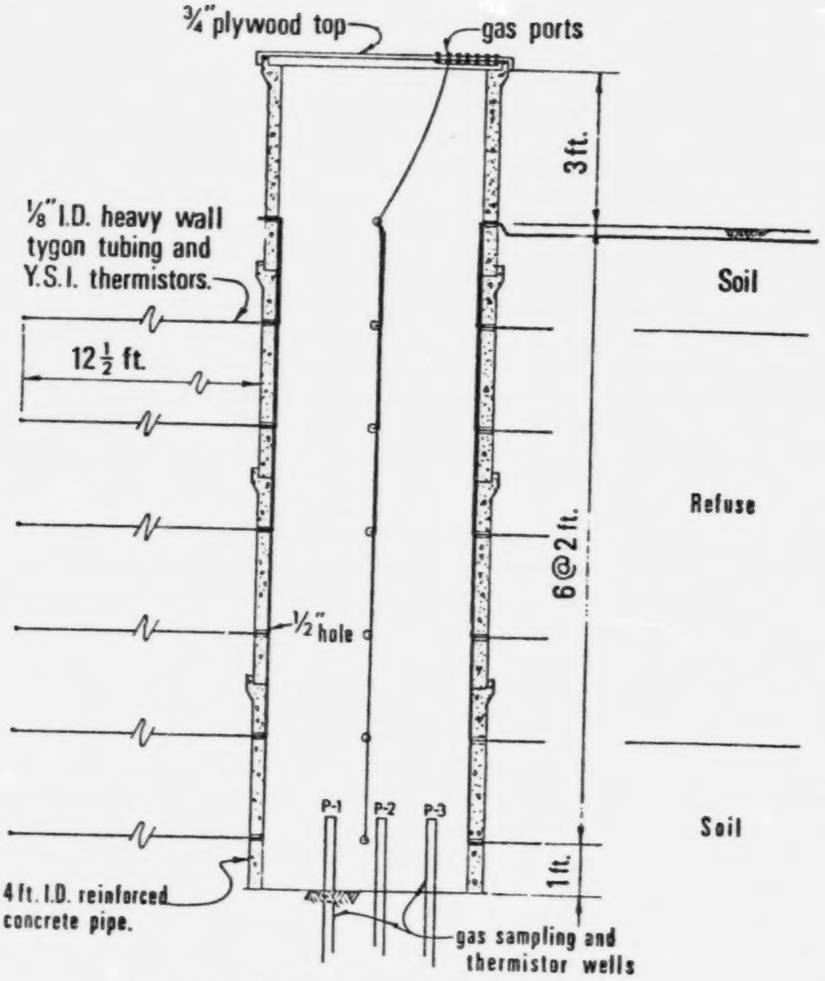
1. Six inches of 1/8 inch (3.175 mm.) to 1/2 inch (12.7 mm.) gravel was placed at the bottom of the hole.

2. Rigid 1-1/4 inch (31.75 mm.) I.D. plastic pipe containing predrilled holes and a neoprene stopper was inserted into the hole. The gas sample tube and thermistor were inserted into and sealed in the stopper. The neoprene stopper was positioned in the tube at the terminal point of the drilled holes. The stopper was sealed in the tube to prevent gas leakage.

3. After pipe insertion, an additional 12 inches (.305 m.) of gravel were placed around the exterior of the pipe.

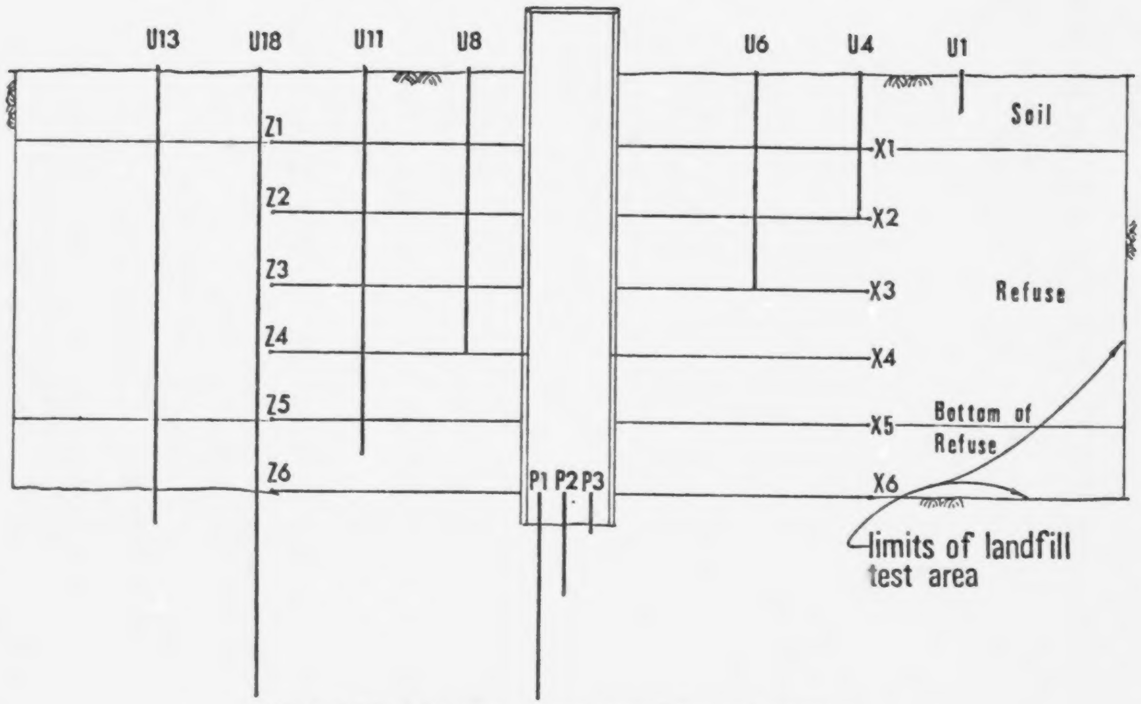
4. A coarse to fine sand pack was placed on top of the gravel to a depth of approximately 5 feet (1.52 m.)

5. The distance from the top of the sand to the ground surface was tightly sealed with Bentonite clay.


¾" plywood top
gas ports
3 ft.
⅛" I.D. heavy wall tygon tubing and Y.S.I. thermistors.
12½ ft.
Soil
Refuse
6@2 ft.
½" hole
P-1
P-2
P-3
Soil
1 ft.
4 ft. I.D. reinforced concrete pipe.
gas sampling and thermistor wells

CROSS SECTION OF CONCRETE PIPE

FIGURE 15



KENNETT SQUARE PLOT SECTION DRAWING

FIGURE 16

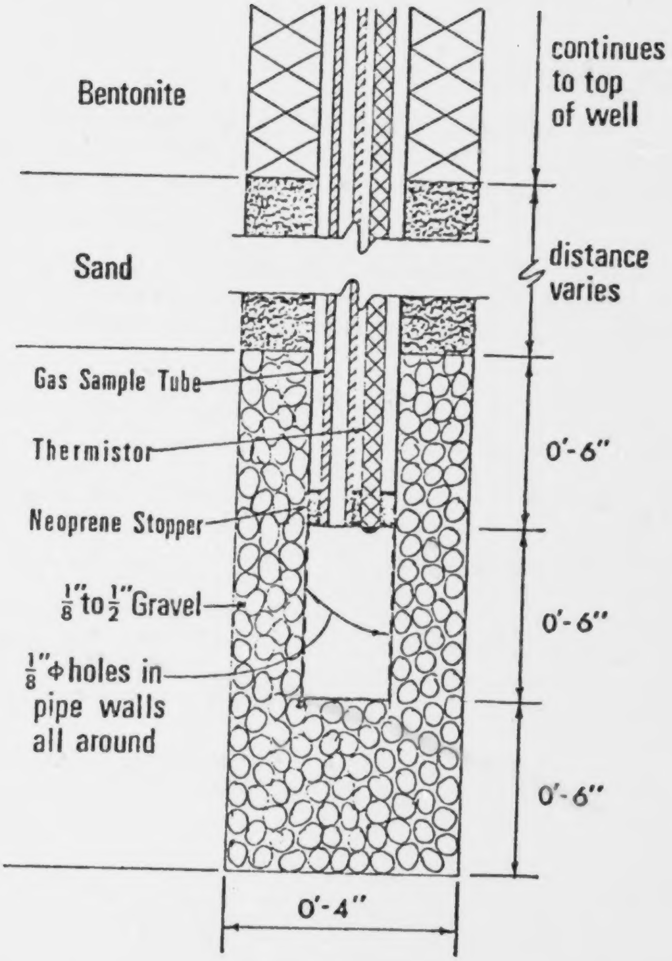
TABLE 7

Sample Depths - Gas and Temperature for Field Facility

Series	Number	Depth Below Original Ground Surface
A through E	1	4 feet
	2	8 feet
	3	13 feet
	4	18 feet
P	1	13 feet
	2	15 feet
	3	18 feet
W through Z	1	2 feet
	2	4 feet
	3	6 feet
	4	8 feet
	5	10 feet
	6	12 feet

Location of Three Additional Temperature Units

1. Water Well No. 11 - Monitors ground water temperature
2. Instrument House - Monitors air temperature
3. Six feet west of instrument house, three inches below soil surface - Monitors soil temperature



DETAILS OF GAS SAMPLING AND THERMISTOR WELLS

FIGURE 17

Temperatures - Temperatures were monitored once every four hours by an automatic scanning-printing system using thermistors and a digital thermometer. The thermistors were positioned at 50 locations throughout the test area. Forty-seven temperature locations corresponded to the gas sample positions listed in Table 7. The three other thermistor locations are also listed in Table 7. The method of installation was the same as described previously under Gas Samples.

Ground Water Samples -

Deep Wells - In August, 1967 fourteen ground water observation wells drilled to a depth of 35 feet (10.67 m.) were located over the site. Their locations are shown in Figure 13.

The ground water wells were located so as to be in the direction of ground water movement, which was predetermined by installation of pilot wells prior to excavation of the main test pit.

The wells consisted of 1-1/4 inch (31.75 mm.) I.D. semi-rigid plastic pipe placed in a 5-1/5 inch (.13 m.) diameter drill hole. The pipes were 35 feet (10.67 m.) long and had 1/8 inch (3.175 mm.) diameter holes drilled along the bottom 9 feet (2.74 m.). The volume of the drill hole exterior to the pipe was gravel packed (1/8 inch (2.175 mm.) to 1/4 inch (6.35 mm.) gravel) to a distance of 1 foot (.305 m.) above the top of the holes. The remaining volume of the space was filled with Bentonite clay to within five feet (1.52 m.) of the soil surface. From the top of the Bentonite to the ground surface, native soil was used to complete the seal.

The sealing procedure insured free passage of suspended solids into the wells, but prohibited entrance of surface water.

Shallow Wells - In August, 1970 shallow depth wells were installed in clusters as shown in Figure 18. The last two numbers of the well designation indicate the depth (in feet) to the bottom of the openings in the well casing. The letters are for designation of location. The porous sections of wells 25 and 27 do not extend to the casing bottom, but cover the section 21 (6.40 m.) to 23 feet (7.01 m.) and 23 (7.01 m.) to 25 feet (7.62 m.) respectively. This was done to permit a cup to be built into the casing bottoms so as to insure accumulation of a sufficient quantity of ground water test samples as the water table fluctuated. Table 8 summarizes the elevations of the top and bottom of each well screen.

SHALLOW WELL CLUSTER LOCATIONS

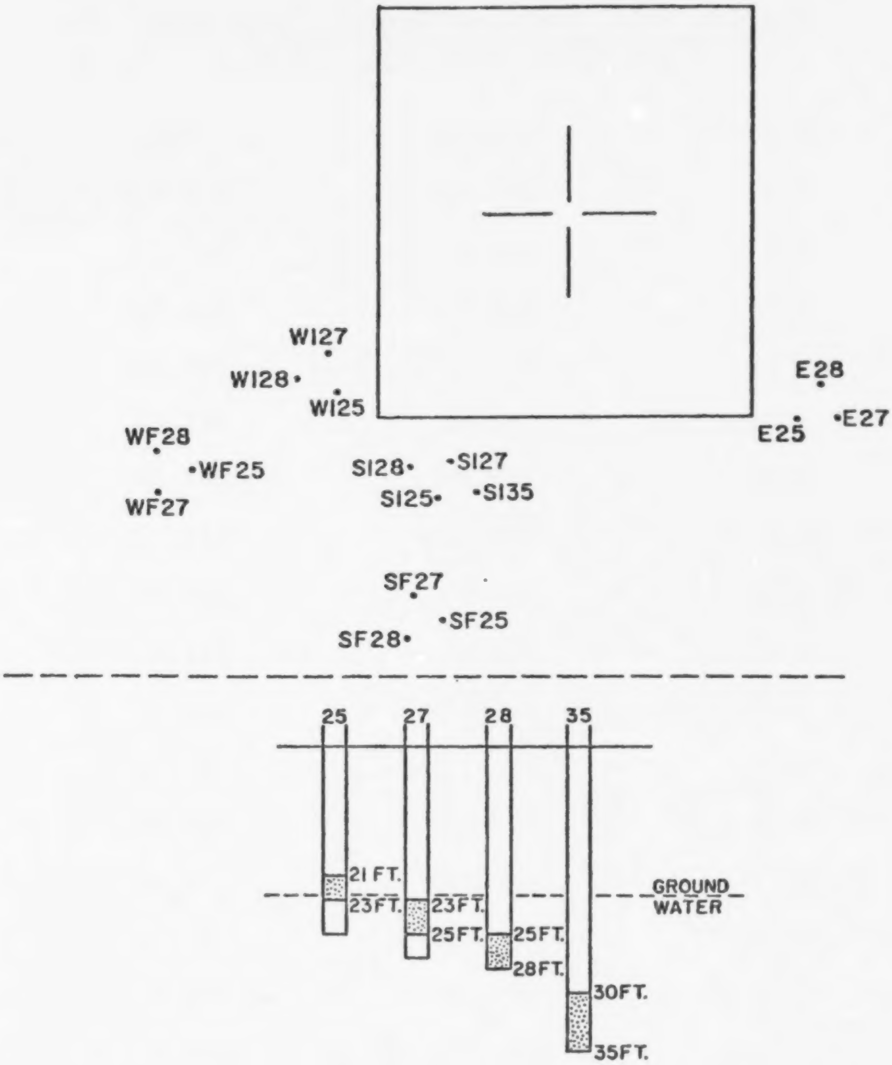


FIGURE 18

TABLE 8

Shallow Well Sampling Screen Elevations (feet above mean sea level)

Well	Bottom	Top
E23	347.45	349.45
E25	345.61	347.71
E28	342.69	345.69
SF23	346.60	348.60
SF25	345.02	347.02
SF28	341.69	344.69
SI23	346.90	348.90
SI25	344.79	346.79
SI28	341.91	344.91
SI35	335.07	340.07
WF23	346.72	348.72
WF25	344.74	346.74
WF28	341.80	344.80
WI23	347.10	349.10
WI25	344.85	346.85
WI28	341.41	344.41

The purpose of the shallow wells was to define the depth and concentration of substantial pollutant migration. The shallow well pattern was established using the data from the deep wells installed in 1967. The method of well installation was as described in the section on Deep Wells.

Unsaturated Soil Water Samples - Water samples were obtained from the soil above the water table and in the refuse by using a soil moisture sampler (Soil-Water Sampler - Soil moisture Equipment Company, Goleta, California; catalog no. 1900).

The sampler contained a "1 bar entry value" porous ceramic cup inserted at the end and cemented to a 1.9 inch (48.26 mm.) I.D. plastic pipe. The open end of the pipe was fitted with a rubber stopper which had provision for application of a vacuum.

Method of placement was the same as for the gas sampling tubes. Locations and depth of soil-water samplers are shown on Figure 16.

Soil Moisture and Density Measurement - Four stainless steel access tubes, 1-5/8 inches (41.28 mm.), I.D., and 0.35 inch (8.89 mm.) wall thickness were located within the landfill and the adjacent undisturbed soil. Each tube was 18 feet (5.49 m.) long. These tubes permitted the measurement of in situ moisture and density. The location of these tubes is shown in Figure 13.

Raingauge - A Belmont No. 551 recording raingauge was located on top of the instrument shed. The location of the instrument shed is shown in Figure 13.

Rain data was recorded continuously on a strip chart controlled by a spring-operated seven-day clock movement.

Instrumentation Schedule -

Inside the Test Landfill Area - The P series gas and temperature units were emplaced after the concrete hub was positioned and prior to the filling operation.

During the filling operation, the tygon lateral gas and temperature units, series W through Z, were located in the fill at the selected depths. The lateral units were extended to a distance of 10.5 feet (3.2 m.) from the face of the concrete hub at each level in each of the four compass directions. After each two feet of refuse was emplaced, trenches were dug for each unit and then backfilled by hand. This procedure insured against injury during the refuse emplacement.

After completion of the filling operation, the two ground water observation wells beneath the landfill area were drilled. Their method of emplacement followed the procedure previously described. Also installed at this time were the unsaturated soil moisture sampling devices and the 1-5/8 (41.28 mm.) inch I.D. standard steel tubes for use in the in situ moisture and density determinations.

Outside the Test Landfill Area - All observation wells, except for the pilot ground water observation wells, were emplaced at the same time as the P series gas and temperature units. The pilot ground water observation wells were established approximately six months prior to excavation of the test pit to permit adequate determination of the direction of ground water movement.

Sample Analysis -

Gas Samples - Samples were obtained weekly and analyzed for carbon dioxide, oxygen, nitrogen, methane, hydrogen sulfide and carbon monoxide using a gas chromatograph. The sampling technique and analytical procedures are described in NTIS Publication No. PB 209 001 and PB 209 002.

Ground Water Samples - Samples were obtained weekly. The analyses performed are listed in Table 2. Analytical procedures are described in NTIS Publication No. PB 209 001 and PB 209 002.

To obtain samples from the shallower wells, a vacuum system was used. A pump, located in the instrument house, was attached to tygon tubing which was lowered into each well to a depth of 25 feet (7.62 m.). The pump was then turned on and the sample was collected in a liter flask and transferred to the sample bottles.

To obtain samples below 28 feet (8.53 m.), a Clayton-Mark sand pump with 3/4 inch (19.05 mm.) I.D. tygon tubing was used. The sand pump operated on the same principle as a bailing bucket with a ball bearing in its housing. As the pump was lowered into the well, the water raised the ball bearing, opening the entrance port. Then, when the pump was pulled from the well, the ball fell back into place and closed the port. The sampling method insured a representative sample with no filtering.

Unsaturated Soil Moisture Samples - A vacuum was applied to the upper end of each tube for a time sufficient to obtain an adequate amount of sample (determined experimentally).

The soil moisture samples accumulated in the bottom of the tube above the porous ceramic cup. They were removed from the tube by a small pump. The samples were analyzed for the same pollutants as the ground water samples.

Refuse Placement

The filling of the test area began on April 29, 1968 and was completed on May 14, 1968. The trench method of sanitary landfilling with horizontal compaction was used. At the end of each day's operation, the refuse was covered with approximately six inches (.15 m.) of soil.

Refuse and daily soil cover were compacted at natural moisture content. The compaction equipment was a Caterpillar Front End Loader, Model No. 955K. This model weighed approximately 16.5 tons (14.98 metric tons) and produced a contact pressure of about 7 pounds per square inch (4921.7 kgs/sq. meter).

The refuse used was primarily domestic with a small percentage of industrial, mainly plastics and cardboard. Collection trucks were primarily compacter type with 16 (12.23) to 20 cubic yard (15.29 cubic meters) capacities. During the filling operation, gross and net weight of each truck was obtained to compute refuse weights and densities. Incoming densities ranged from a minimum of 150 pounds per cubic yard (89 kgs/cu.meter) to a maximum of 700 pounds per cubic yard (415.33 kgs/cu.meter). Average density was 500 pounds per cubic yard (296.67 kgs/cu.meter).

Total weight of emplaced refuse was 274 tons (248.7 metric tons). Neglecting the 6 inch (.152 m.) daily soil cover, the compacted density of the fill was 740 pounds per cubic yard (439.07 kgs/cu.meter) for a compaction ratio of 1.5 to 1.

The estimated total thickness of intermediate soil covers used at the end of each day's filling was 1.4 feet (.43 m.). Using a net height of 6.6 feet (2.01 m.) for refuse gave an adjusted initial unit weight of 895 pounds per cubic yard (531.03 kgs/cu.meter).

A random sampling technique was used to obtain representative refuse samples. The chemical composition of the emplaced refuse, based on these composite samples, is given in Table 9.

TABLE 9

Kennett Square Initial Solid Waste Chemical Analysis (mg/g of refuse - except as noted)

Percent Ether Extracted	1.70
Percent Water Extracted	7.68
Solid COD	12.62
Solid Nitrogen	3.43
Water Soluble	
Iron	0.221
Zinc	0.589
Nickel	0.053
Copper	0.023
Calcium	0.945
Phosphate	0.312
Chloride	1.532
Sodium	1.324
Ammonia Nitrogen	0.0
Organic Nitrogen	0.382
Chemical Oxygen Demand	43.98

LABORATORY SANITARY LANDFILL MINI-LYSIMETER

Mini-Lysimeter Description

The laboratory mini-lysimeters were 55 gallon (208 liter) drums (Figure 19) constructed as simplified versions of the full size laboratory lysimeter.

The tank sides were insulated with six (6) inches (.152 m.) of fiberglass insulation. However, the top and bottom of the tank were exposed to ambient temperatures. To minimize temperature fluctuation influences, the drums were located in a controlled temperature room set at 65°F. As shown in Figure 19, leachate collection was from the bottom of the tank and gas samples were collected from mid-height on the tank side.

Milled Refuse Composition, Size and Placement

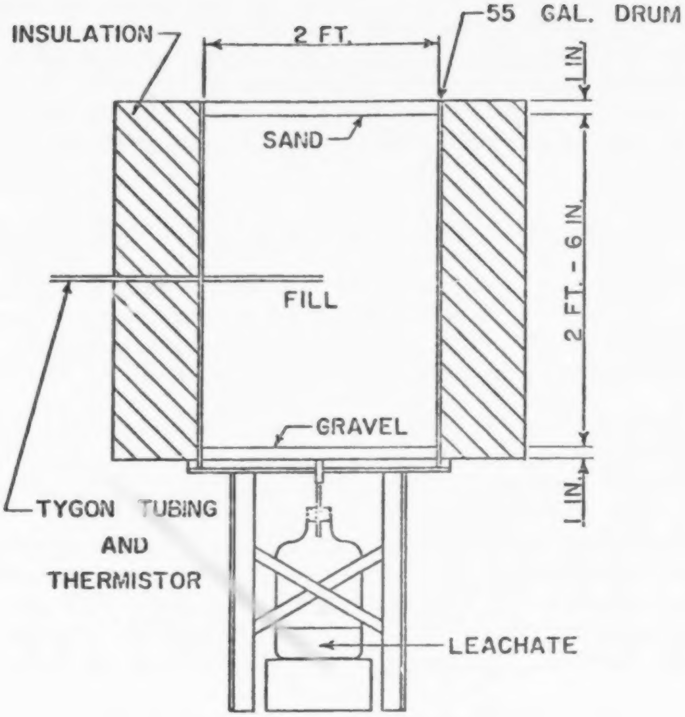
Eight mini-lysimeters were used in the study. Each unit was filled with domestic refuse obtained from a local collector. Refuse composition before milling is summarized in Table 10 and placement data is presented in Table 11.

Five sizes of milled refuse were used in the study. Three of the gradations were produced using a Williams Type GP 1518 Hammermill operating at 3600 RPM with grate openings of one inch and hammer spacing of one-half inch. The larger size particles were obtained by modifying the mill. Modification consisted of enlarging the grate spacing and reducing the number of hammers. The milled refuse size used in each mini-lysimeter is summarized in Table 11 and described in detail in the paragraphs which follow.

A mechanical sieve analysis of each ground refuse size was performed. The gradation curves are presented in Figure 20. The D_{50} sizes are also listed in the figure. D_{50} is the fifty percent finer equivalent diameter for the refuse.

The gradation curves are similar to those of soils. However, basic differences in particle structure can be observed visually. Size A has two distinctly different shaped particles. The lighter materials such as paper, film plastic and cloth are needle shaped whereas the heavier material such as soil, metal and glass tends to be spherical shaped.

Sizes B and C show the same basic differences as A except that the lighter materials are plate shaped rather than needle shaped. Sizes D and E are erratic in shape with the larger particles tending to be the lighter weight.



MINI LYSIMETER SCHEMATIC
FIGURE 19

TABLE 10

Composition of Refuse Used in Mini-Lysimeters

Component	Percent by As-Received Weight
Paper	55
Rags	3
Metal	10
Plastics and Rubber	3
Wood	2
Organics (Food Wastes & Garden Wastes)	15
Ashes and Dirt	2
Glass	10

TABLE 11

Mini-Lysimeter Refuse Placement Data

Lysimeter	D_{50} Size (mm.)	Density lbs/yd^3	Depth (ft.)	Original Moisture Content (% Dry Weight)	Estimated* Field Capacity (inches/ft)
J	4.80	515	2.4	20.3	5.8
K	3.20	520	2.4	16.5	8.2
M	3.20	505	2.5	16.6	8.1
N	3.20	740	2.7	16.5	9.2
O	3.20	650	2.5	16.7	8.8
P	92.00	520	2.7	20.5	4.0
R	0.89	530	2.5	8.55	9.1
S	13.50	519	2.7	20.5	5.8

*Estimated from Figure 83 Field Capacity vs Density for Various Component Sizes (saturated samples)

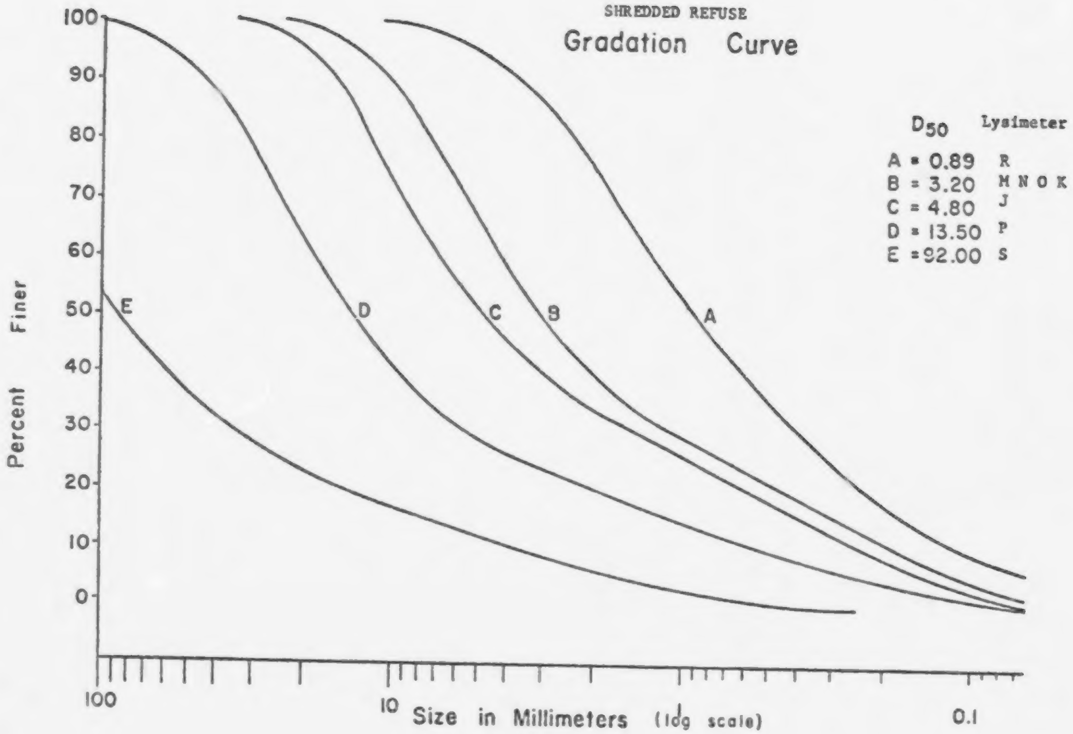

SHREDDED REFUSE
Gradation Curve
D50 Lysimeter
A = 0.89 R
B = 3.20 M N O K
C = 4.80 J
D = 13.50 P
E = 92.00 S
Percent Finer
100
90
80
70
60
50
40
30
20
10
0
A
B
C
D
E
100
10
0.1
Size in Millimeters (log scale)

FIGURE 20

The effect of milling on the initial refuse composition was evaluated. The purpose of the evaluation was to establish whether or not the grinding process would alter the refuse organic component due to the increase in temperature resulting from the grinding action. It was hypothesized that the increase in temperature due to the mechanical action would volatilize much of the easily metabolized materials such as sugars, starches and food proteins which have low boiling points. Samples of the ground refuse were chemically analyzed immediately after milling. The chemical analyses were performed using the procedures recommended by Schoenberger(5) and included:

1. Chemically Decomposable Oxygen
2. Nitrogen
3. Percent Ether Extractable
4. Percent Water Extractable

The water extractable portion was analyzed using procedures reported by A.A. Fungaroli in Pollution of Subsurface Water by Sanitary Landfills, U.S. Environmental Protection Agency, SW-12rg, Washington D.C. 1971.

The results of the analysis are given in Table 12. It can be seen by the results that the hypothesis proved to be valid. Both the chemical decomposable organic content and the ether soluble fraction of the milled refuse decreased with decreasing particle size (hence increasing energy input during grinding).

The only inorganic component which was found to be altered by the milling process was iron. Iron increased almost 50 percent in the A size. The increase in iron occurs because iron is the only metallic ion measured whose surface area will be increased by milling. Since the surface area of iron is increased by milling, the soxhlet extraction which is time dependent will remove more iron from the smaller sizes. Since it is assumed that the same amount of iron is present in all the refuse sizes, these results indicate that initially the iron concentrations of the fine ground refuse would be higher than the coarser ones.

All other analyses indicate statistically (analysis of variance - F test) that the refuse is from the same population. The results of these analyses are given in Table 12 along with the mean value of all the tests and the F-statistics for each analysis. The results which show variations are designated by asterisks. The Duncan comparison test was performed to determine sizes which differed.

The refuse was hand placed and compacted into the mini-lysimeters. Except for mini-lysimeter P, refuse placement

TABLE 12

Milled Refuse Analysis
(mglg Refuse except where noted)

Milled Refuse Size	A	B	C	D	E	Avg. Mean	F Statistic
D_{50}	0.89	3.20	4.80	13.50	92.00		
CDO (mg 0/gram refuse)	398	602	781	933	979	-	29.94*
Percent Ether Extractible	1.76	2.01	1.93	3.59	4.03	-	10.03*
Percent Water Extractible	7.76	4.94	4.40	4.25	6.05	5.48	3.103
Nitrogen (mg N/gram refuse)	4.76	4.11	5.20	4.27	5.26	4.72	1.598
Water Extractible Portion							
Phosphate	0.97	0.78	0.64	0.45	0.44	0.65	2.49
Sulfate	7.76	8.14	8.10	7.10	8.13	7.85	0.51
Iron	0.64	0.087	0.11	0.04	0.03	-	57.83*
Nickle	0.007	0.009	0.01	0.003	0.006	0.007	0.81
Copper	0.016	0.010	0.013	0.007	0.012	0.012	2.34
Zinc	0.027	0.037	0.048	0.023	0.024	0.032	4.00
Magnesium	0.194	0.181	0.173	0.125	0.125	0.166	1.298
Calcium	0.769	0.435	0.739	0.352	0.672	0.593	3.07
Sodium	2.269	1.970	1.875	2.445	1.991	2.11	0.626
Potassium	1.212	1.032	0.947	0.846	1.132	1.034	1.041
Total Alkalinity	0.474	1.820	2.023	1.767	1.691	-	19.84*
Chloride	2.581	2.300	2.345	2.087	2.759	2.414	0.56
Hardness	4.149	2.037	2.491	1.520	2.435	-	16.27*
pH	5.86	6.17	6.16	6.10	5.90	6.03	1.72
Specific Conductance (micromhos)	452	221	233	226	226	-	27.68*

*Statistical difference in mean values.

was routine. Lysimeter P was filled with unground refuse and some placement difficulties due to material size were encountered. Where necessary, the unground refuse size was decreased to overcome the placement problems.

Refuse Moisture Control

After refuse placement, water was added to each unit to bring the refuse to one-half of field capacity. Thereafter, water was fed to the units, except M, at the rate of 2.28 liters per week. The quantity of water added per week was the weekly precipitation minus evapo-transpiration for southeastern Pennsylvania. Mini-lysimeter M was fed water following the same schedule as the large laboratory lysimeter.

SECTION 4

EXPERIMENTAL RESULTS

SANITARY LANDFILL LABORATORY LYSIMETER

Experimental data were obtained for a period of approximately 1600 days starting on October 1, 1967. The results are presented in graphical form in this section. The tabulated data for the last half of the study are available in Volume 2 of this report. The tabulated data for the first half of the study are available as an appendix to the previous report. (SW-12rg-Pollution of Subsurface Water by Sanitary Landfills, U.S. Environmental Protection Agency, 1971).

Figure 21 represents the volume of water added at the top of the lysimeter and the leachate removed at the bottom. Shown in Figure 22 is the curve for the water stored in the lysimeter (amount added minus quantity of leachate). Leachate pH values are given in Figure 23. Curves for concentration and total quantities leached of iron, zinc, phosphate, sulfate, chloride, sodium, nitrogen, hardness, chemical oxygen demand, total solids, suspended solids, nickel and copper are presented in Figures 23 through 52. In most cases, curves extend for the test period. However, where early termination or breaks in the curves occur, this is due either to analysis termination because of lack of substance concentration or lack of confidence in the analysis.

In addition to the complete set of curves, the data were analyzed for mean and standard deviation for each low and high quantity of leachate period. The results of these analyses are presented in Figures 53 through 69. Correlations of the various parameters were also performed. The results of the correlations are presented in Tables 13 through 19. (See Summary).

Leachate Quantity

The curves in Figure 21 show the influence of initial water content and the programmed water feeding schedule on leachate production. The curves graphically indicate the initial lag between water addition and leachate production.

The generation of substantial quantities of leachate required that each lysimeter component be at their respective field

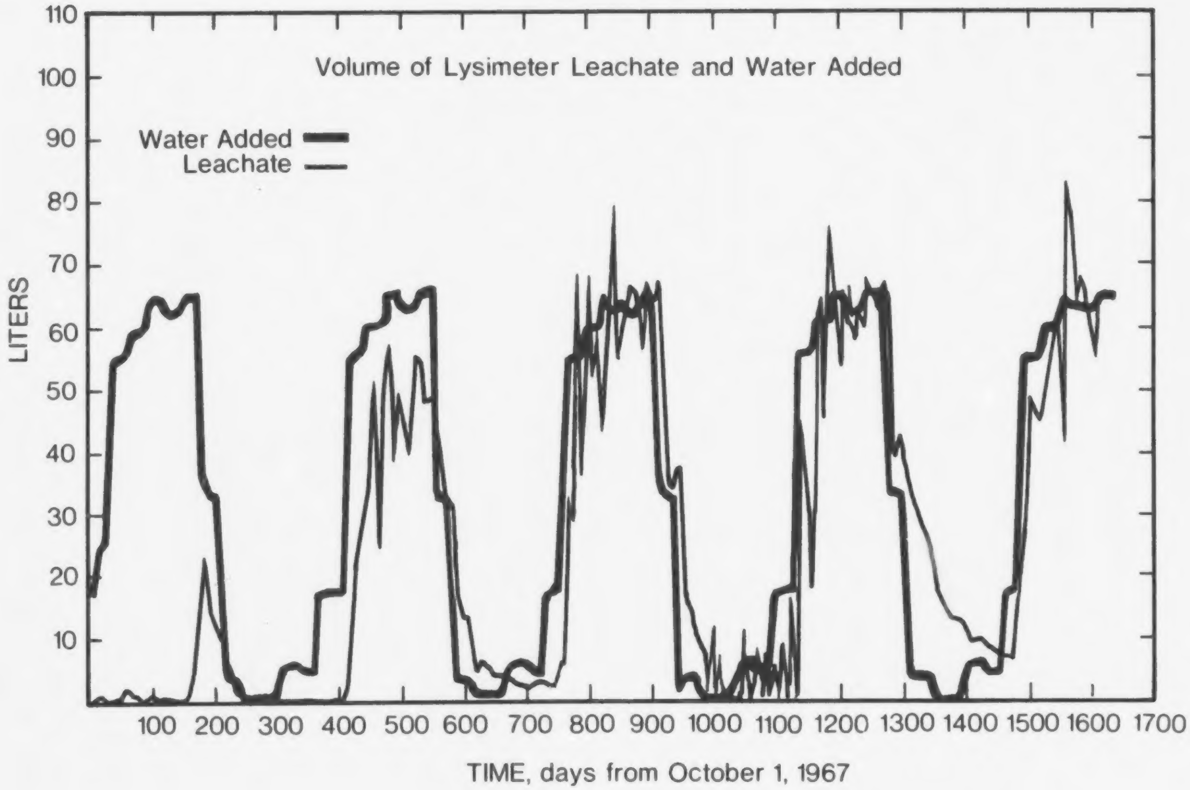
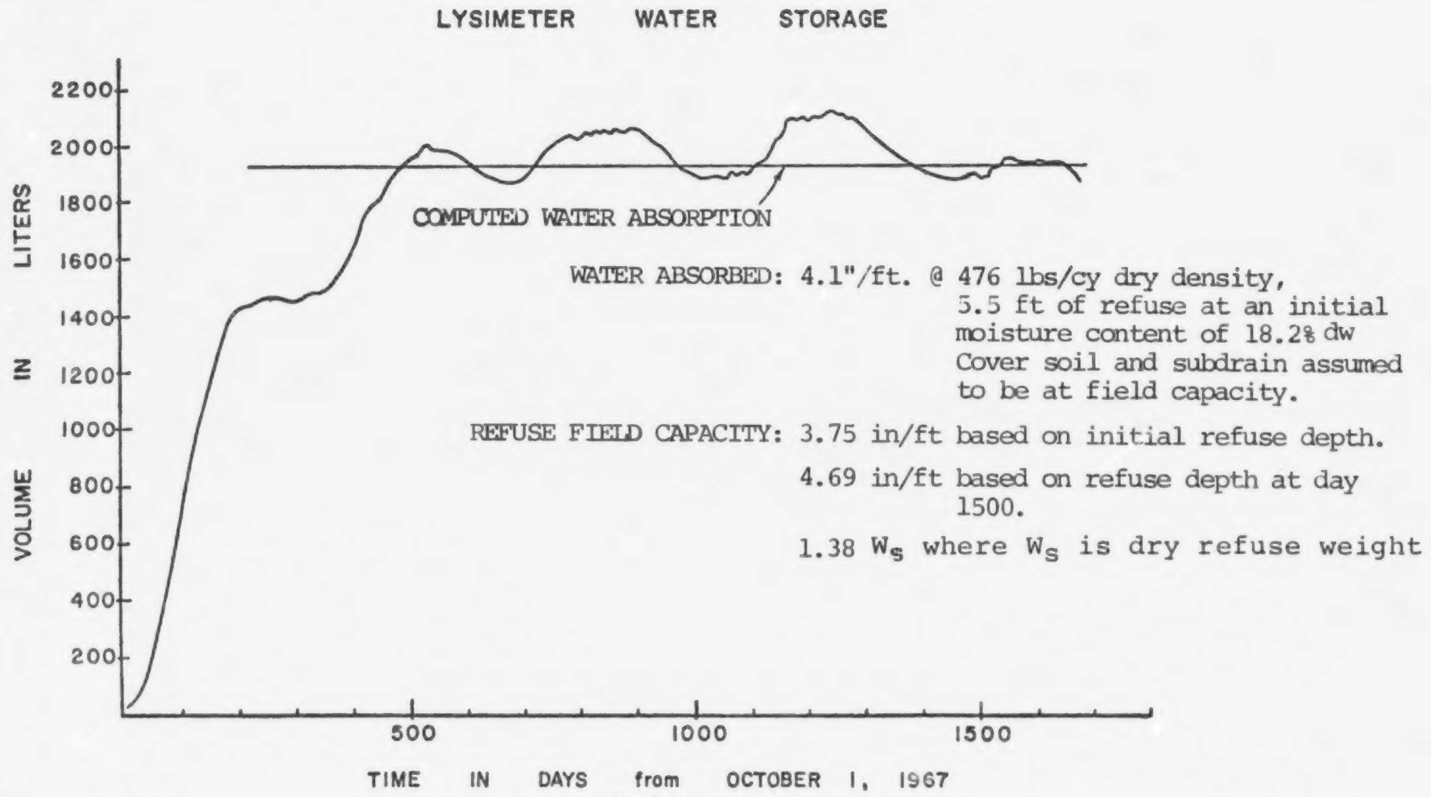

Volume of Lysimeter Leachate and Water Added
Water Added
Leachate
LITERS
110
100
90
80
70
60
50
40
30
20
10
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
TIME, days from October 1, 1967

Figure 21



WATER ABSORBED: 4.1"/ft. @ 476 lbs/cy dry density, 5.5 ft of refuse at an initial moisture content of 18.2% dw Cover soil and subdrain assumed to be at field capacity.

REFUSE FIELD CAPACITY: 3.75 in/ft based on initial refuse depth.

4.69 in/ft based on refuse depth at day 1500.

1.38 W_s where W_s is dry refuse weight

FIGURE 22

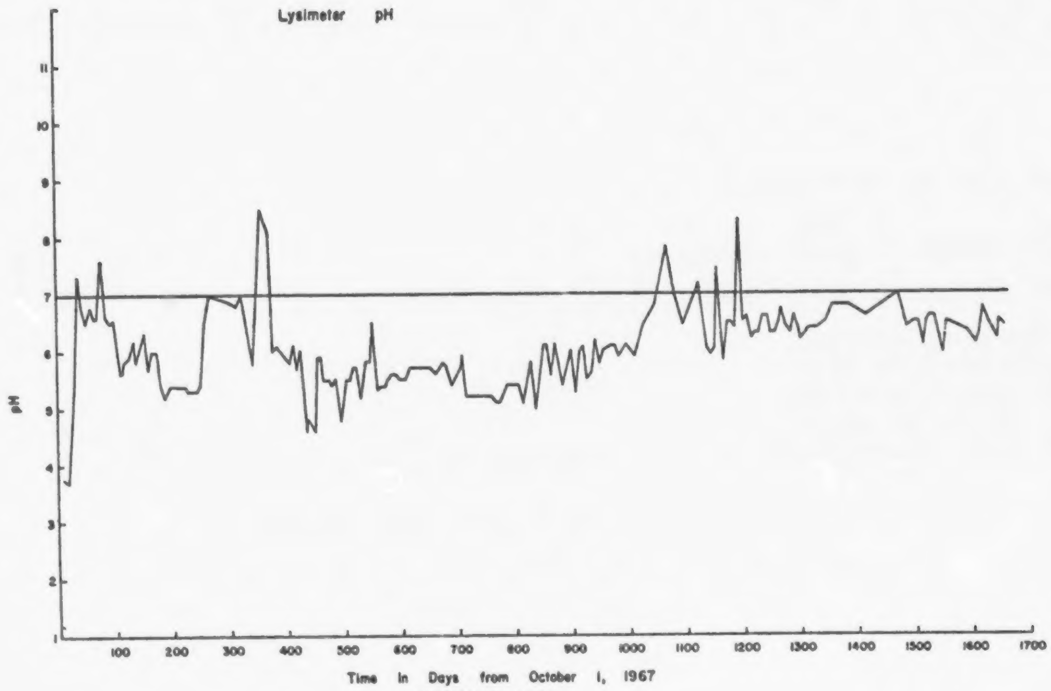

Lysimeter pH
pH
1
2
3
4
5
6
7
8
9
10
11
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 23

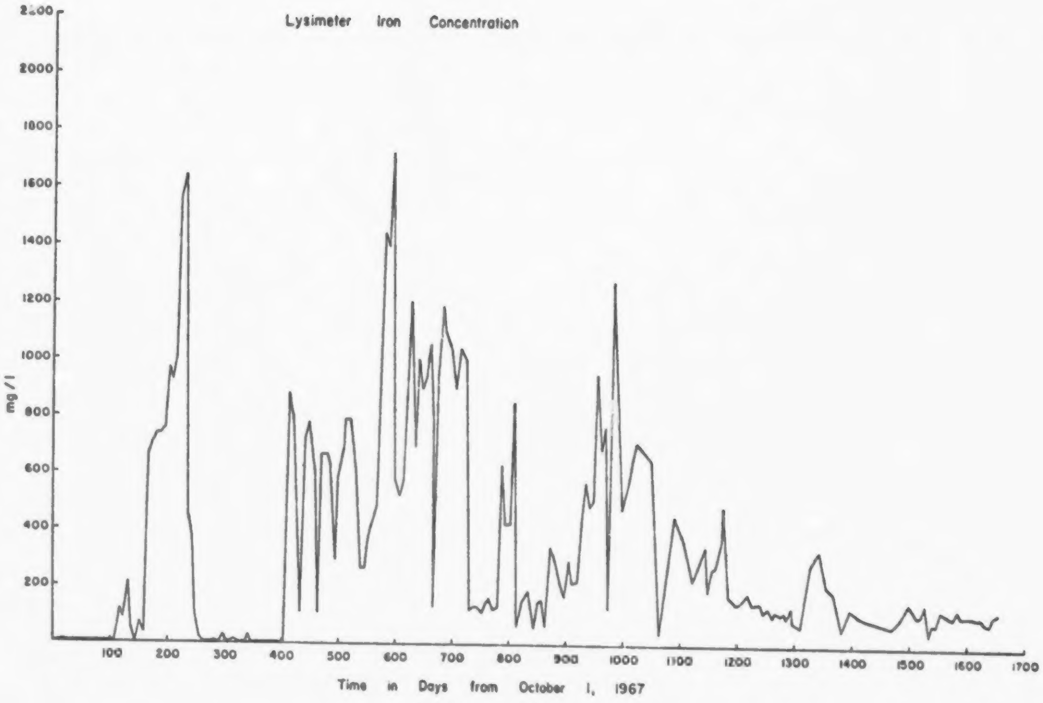

Lysimeter Iron Concentration
mg/l
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 24

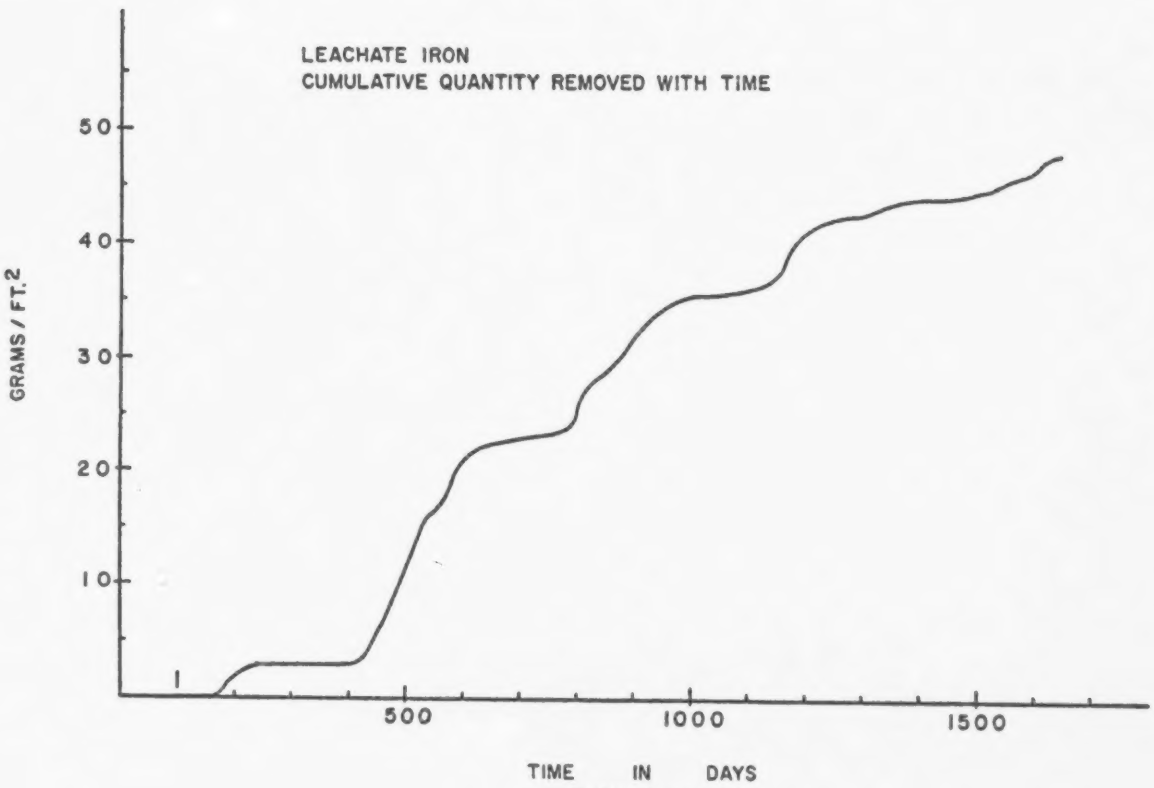

LEACHATE IRON
CUMULATIVE QUANTITY REMOVED WITH TIME
GRAMS / FT.²
50
40
30
20
10
I
500
1000
1500
TIME IN DAYS

FIGURE 25

LEACHATE IRON
CUMULATIVE GRAMS / FT.^{2} REMOVED
VS. QUANTITY OF LEACHATE / FT.^{2}

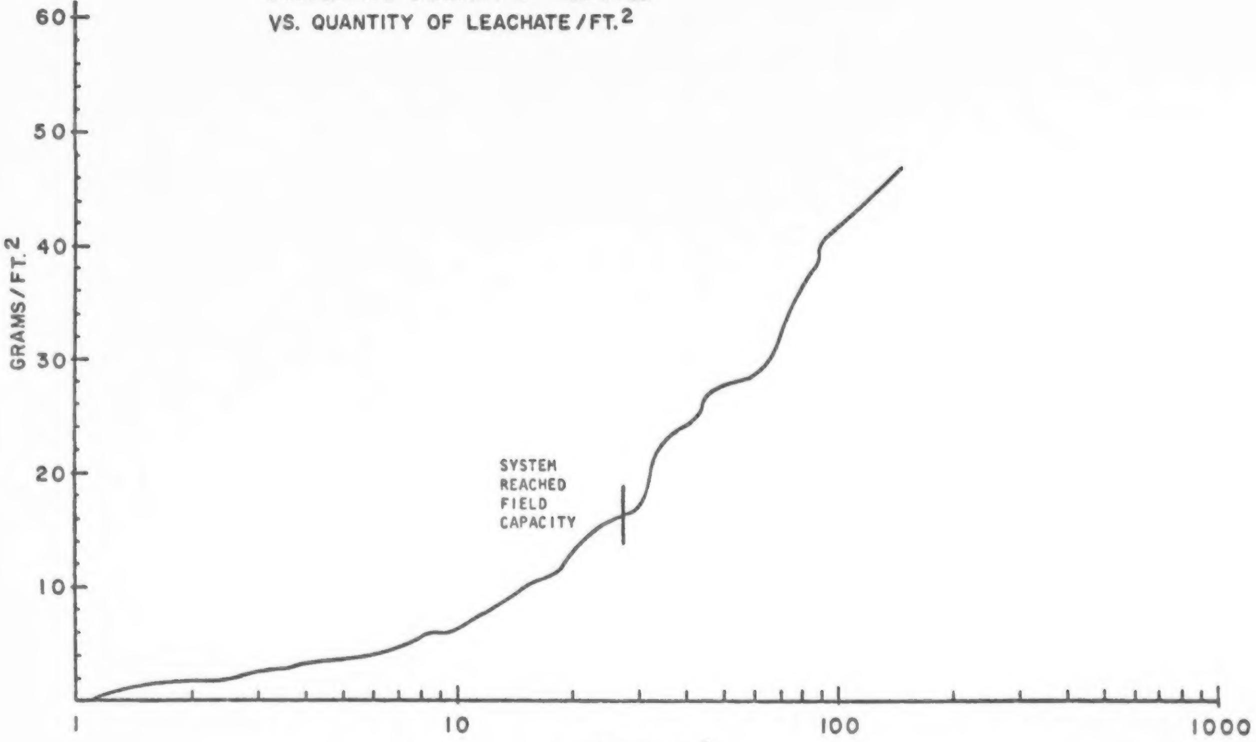
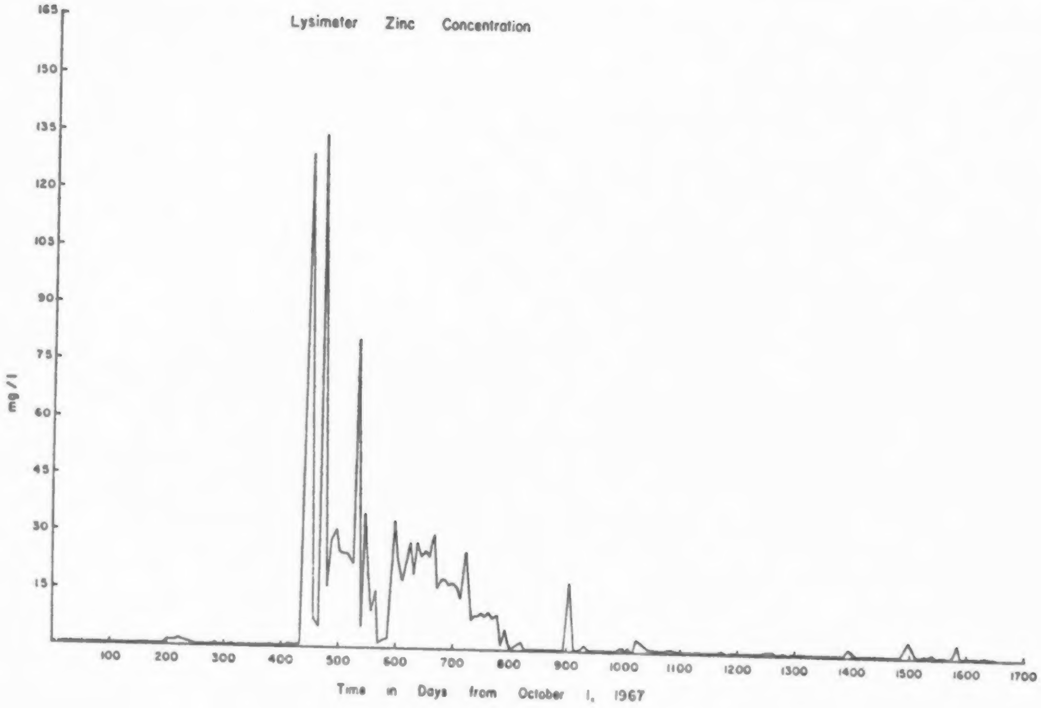
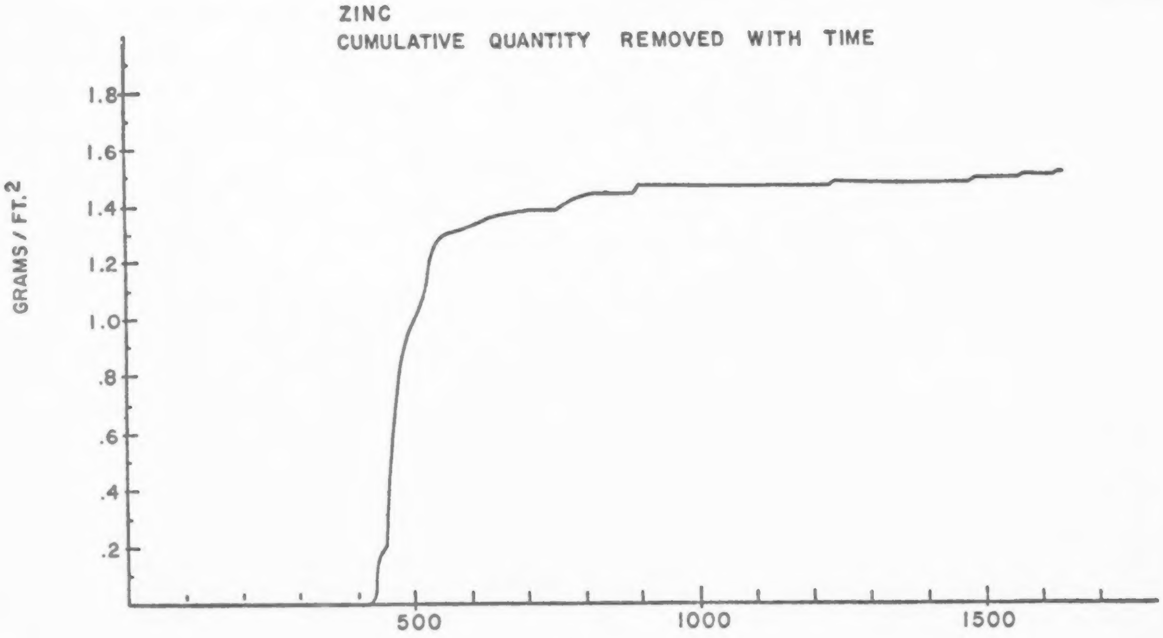


Figure 26



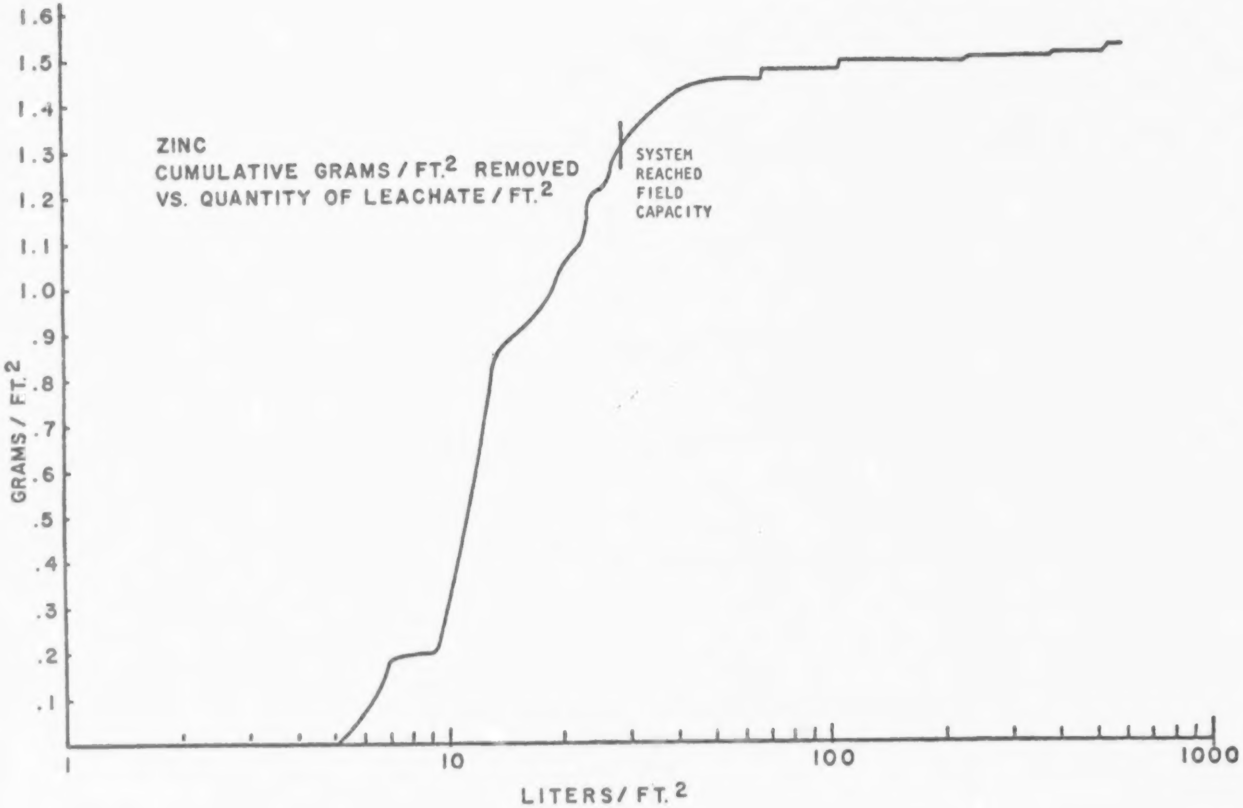
Lysimeter Zinc Concentration

FIGURE 27



ZINC
CUMULATIVE QUANTITY REMOVED WITH TIME

FIGURE 28



ZINC
CUMULATIVE GRAMS / FT.^{2} REMOVED
VS. QUANTITY OF LEACHATE / FT.^{2}

FIGURE 29

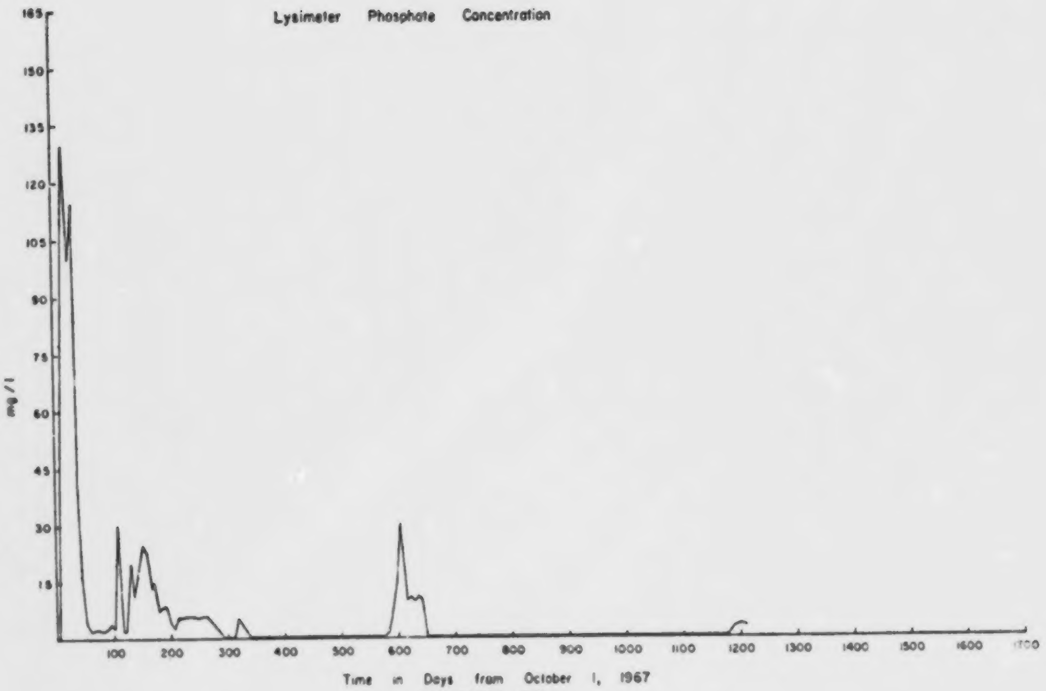

Lysimeter Phosphate Concentration
mg / l
165
150
135
120
105
90
75
60
45
30
15
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 30

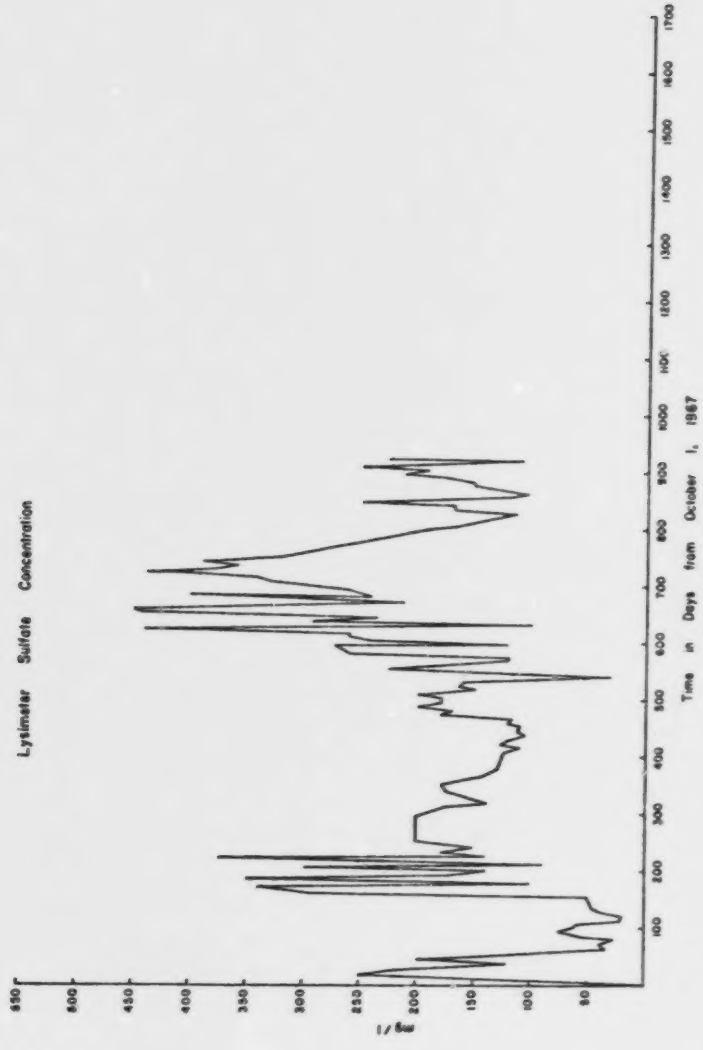

Lysimeter Sulfate Concentration
mg/l
550
500
450
400
350
300
250
200
150
100
50
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 31

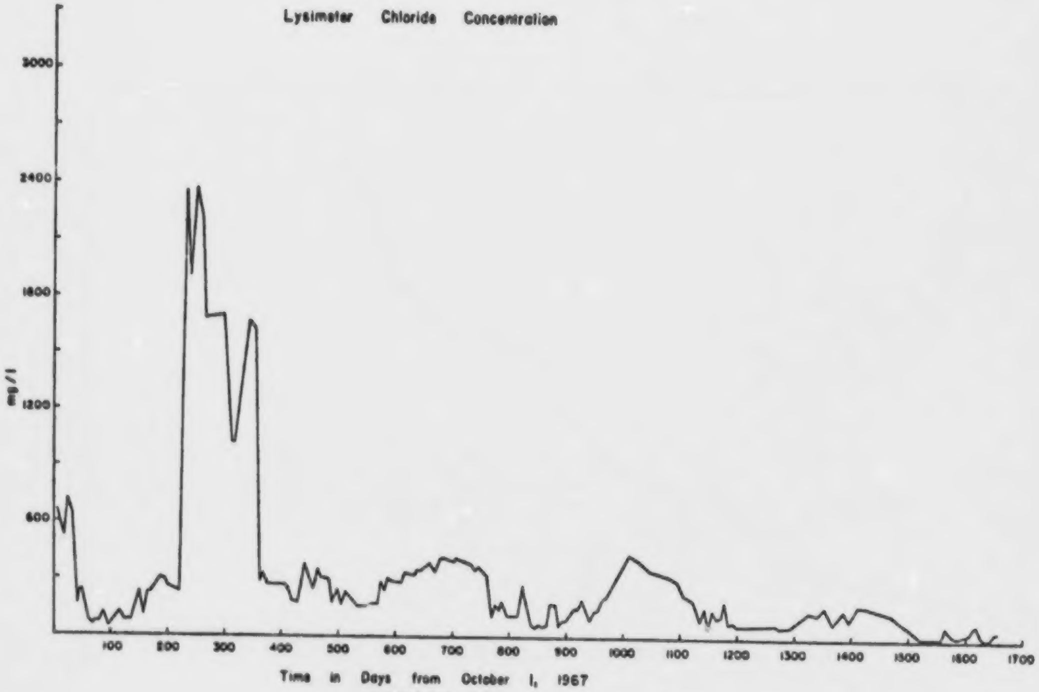
Lysimeter Chloride Concentration
mg/l
3000
2400
1800
1200
600
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 32

CHLORIDE
CUMULATIVE QUANTITY REMOVED WITH TIME

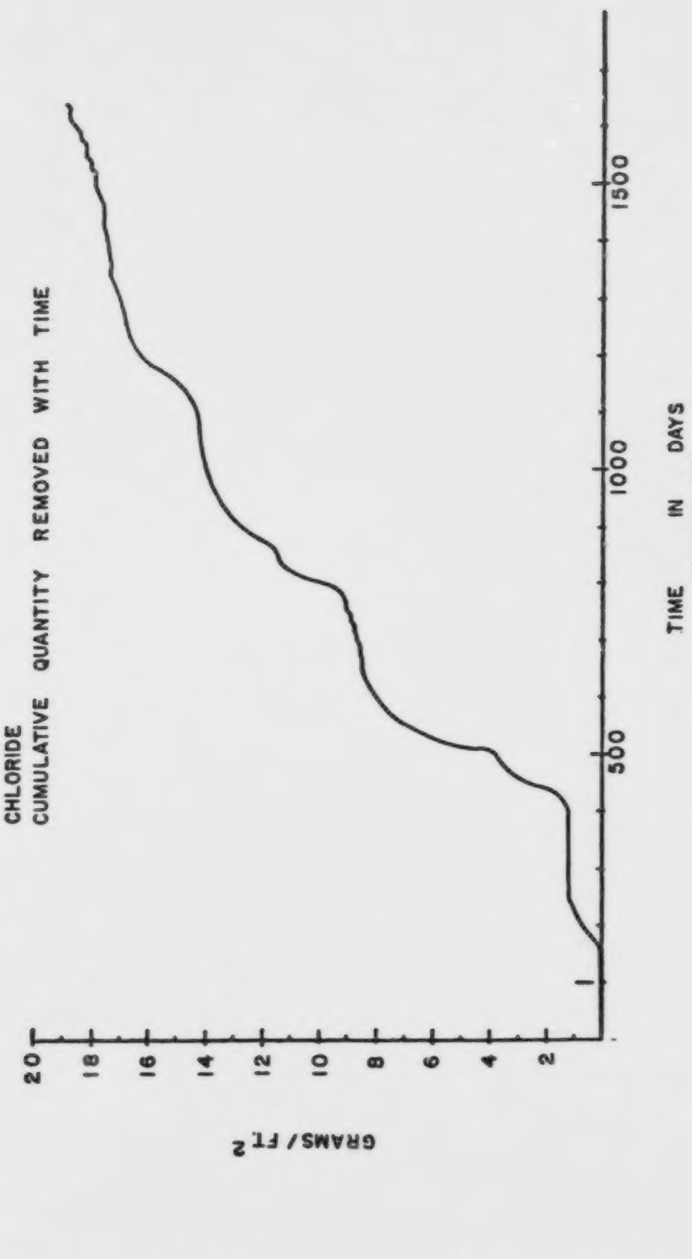


FIGURE 33

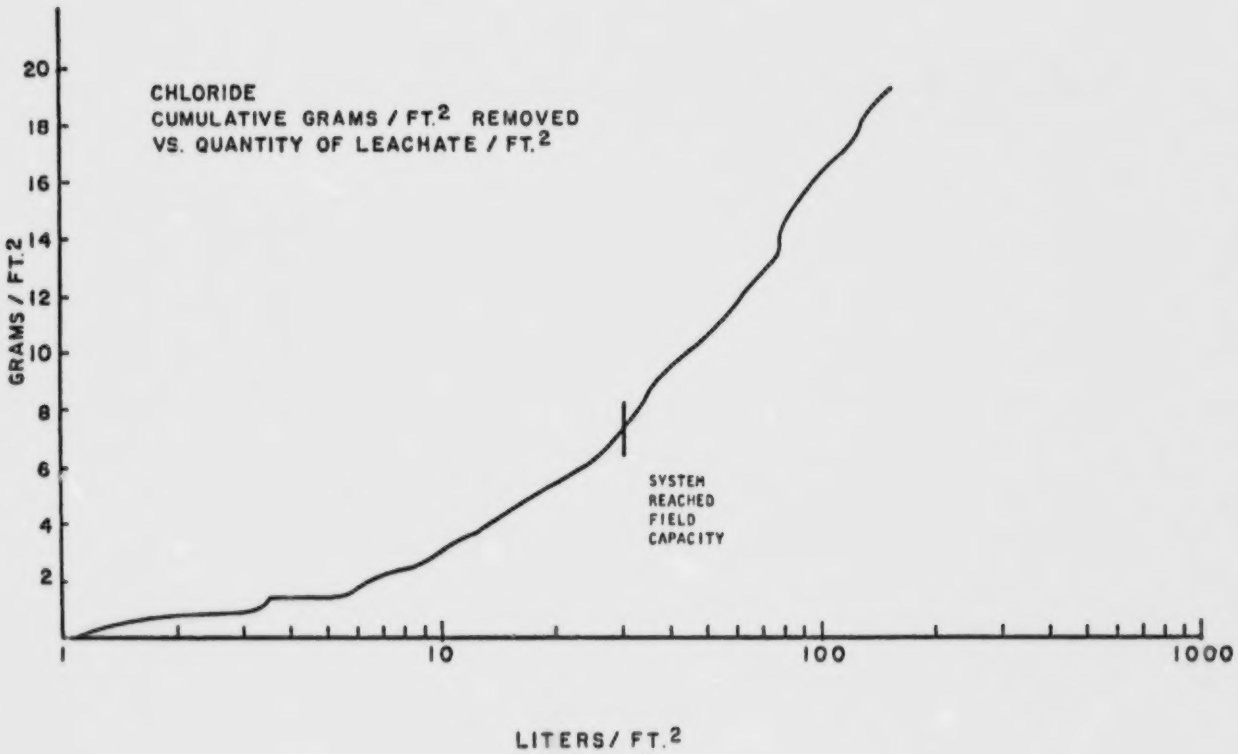

CHLORIDE
CUMULATIVE GRAMS / FT.^{2} REMOVED
VS. QUANTITY OF LEACHATE / FT.^{2}
GRAMS / FT.^{2}
20
18
16
14
12
10
8
6
4
2
SYSTEM
REACHED
FIELD
CAPACITY
1
10
100
1000
LITERS/ FT.^{2}

FIGURE 34

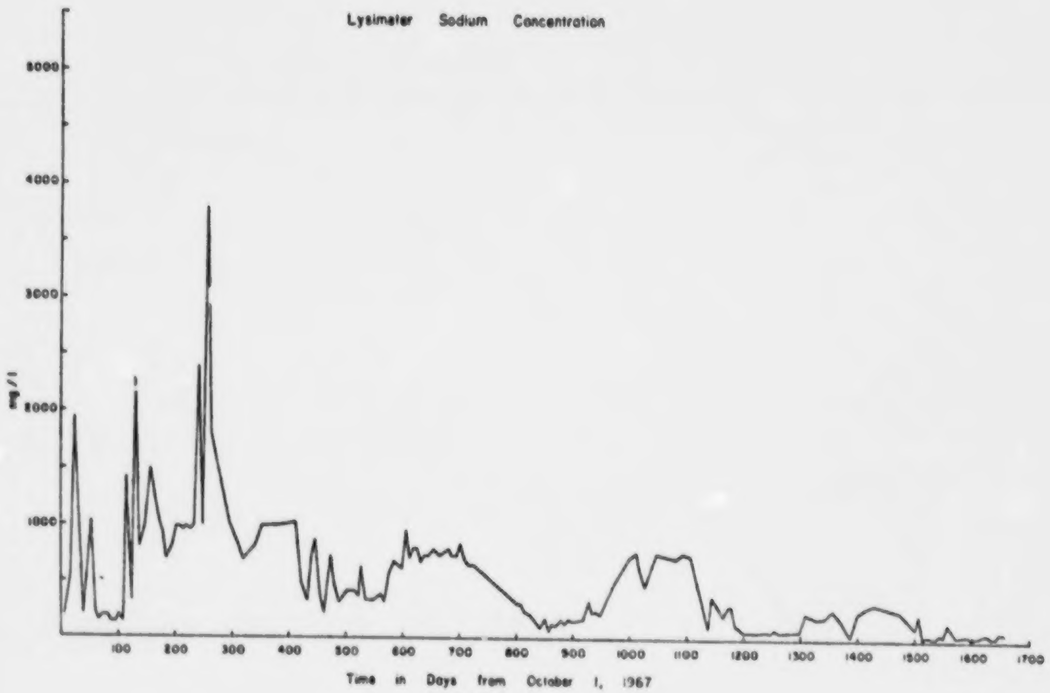
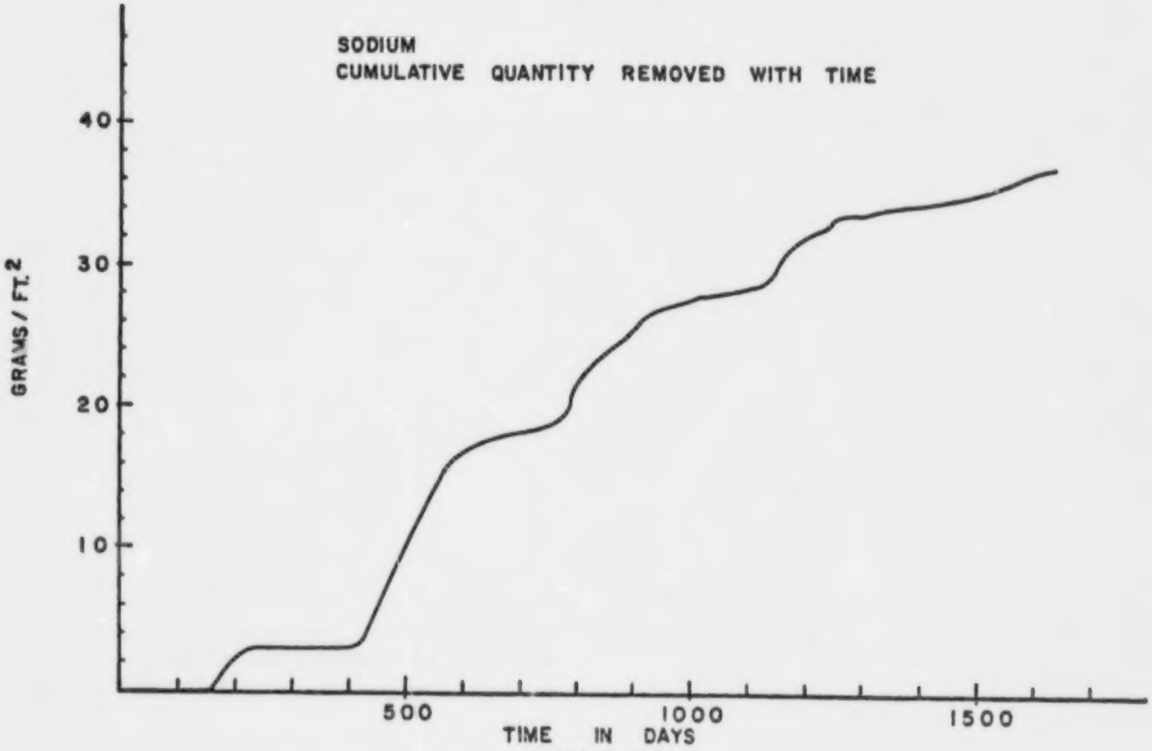
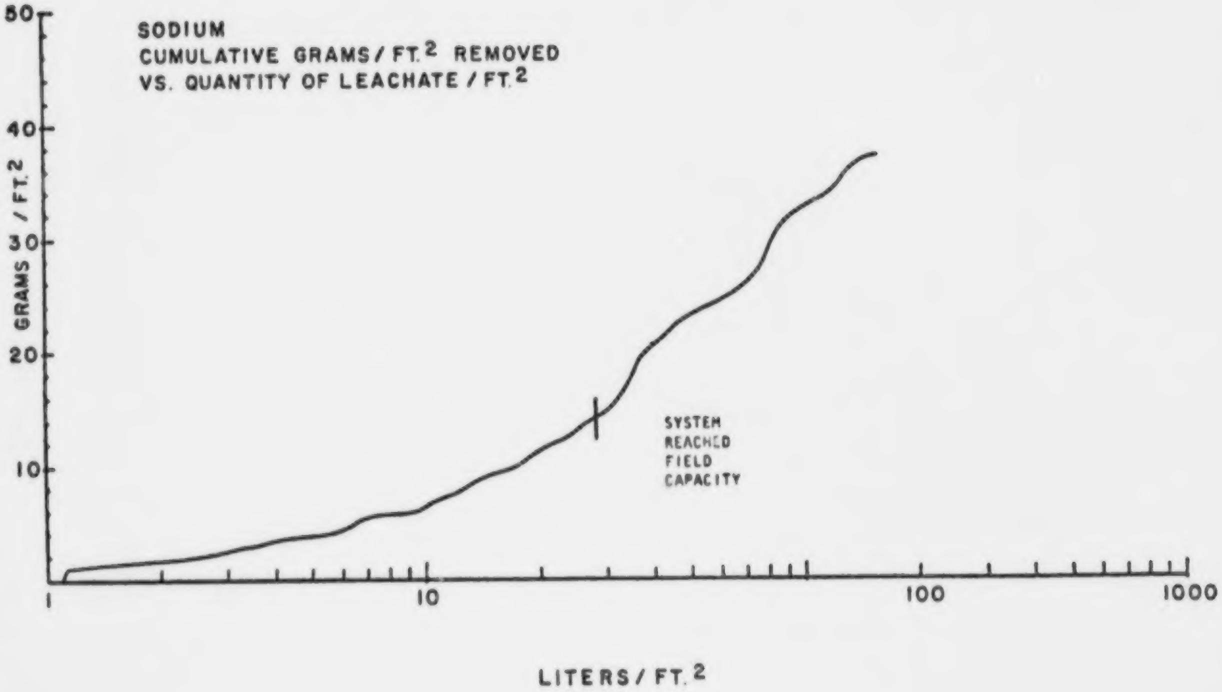

Lysimeter Sodium Concentration
5000
4000
3000
2000
1000
mg/l
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 35



SODIUM
CUMULATIVE QUANTITY REMOVED WITH TIME

FIGURE 36



SODIUM
CUMULATIVE GRAMS / FT.^{2} REMOVED
VS. QUANTITY OF LEACHATE / FT.^{2}

FIGURE 37

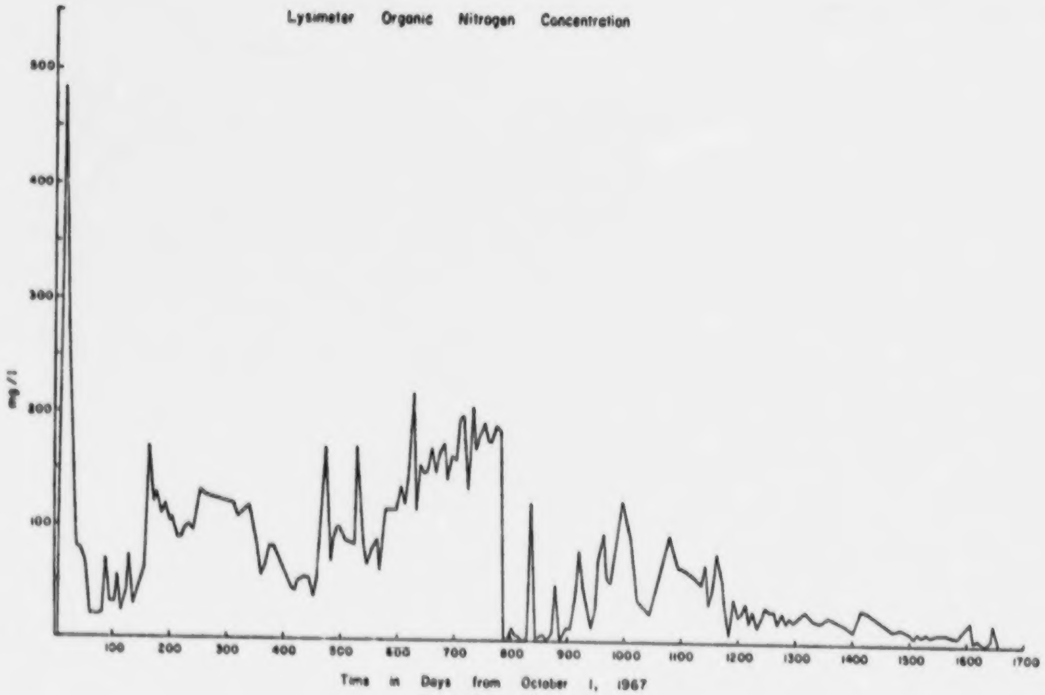

Lysimeter Organic Nitrogen Concentration
mg/l
500
400
300
200
100
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 38

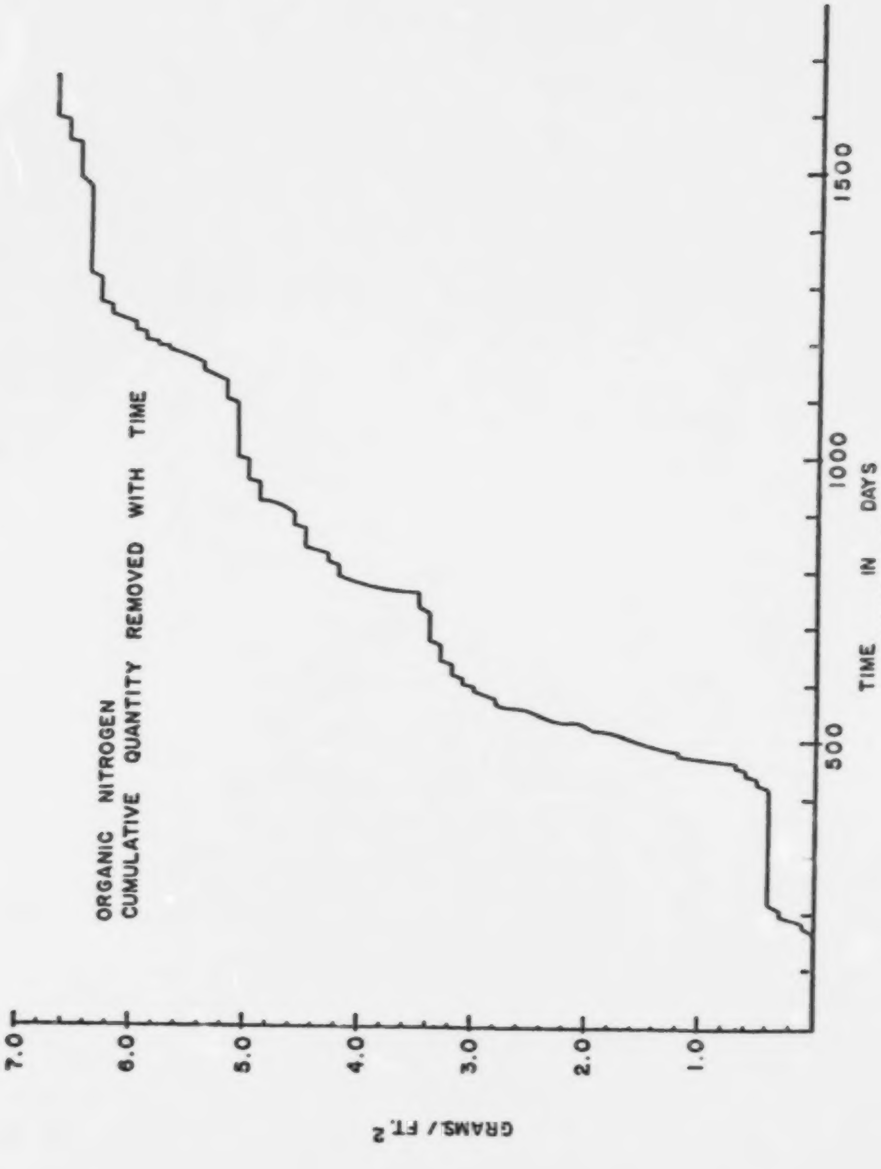

ORGANIC NITROGEN
CUMULATIVE QUANTITY REMOVED WITH TIME
GRAMS / FT.^{2}
7.0
6.0
5.0
4.0
3.0
2.0
1.0
500
1000
1500
TIME IN DAYS

FIGURE 39

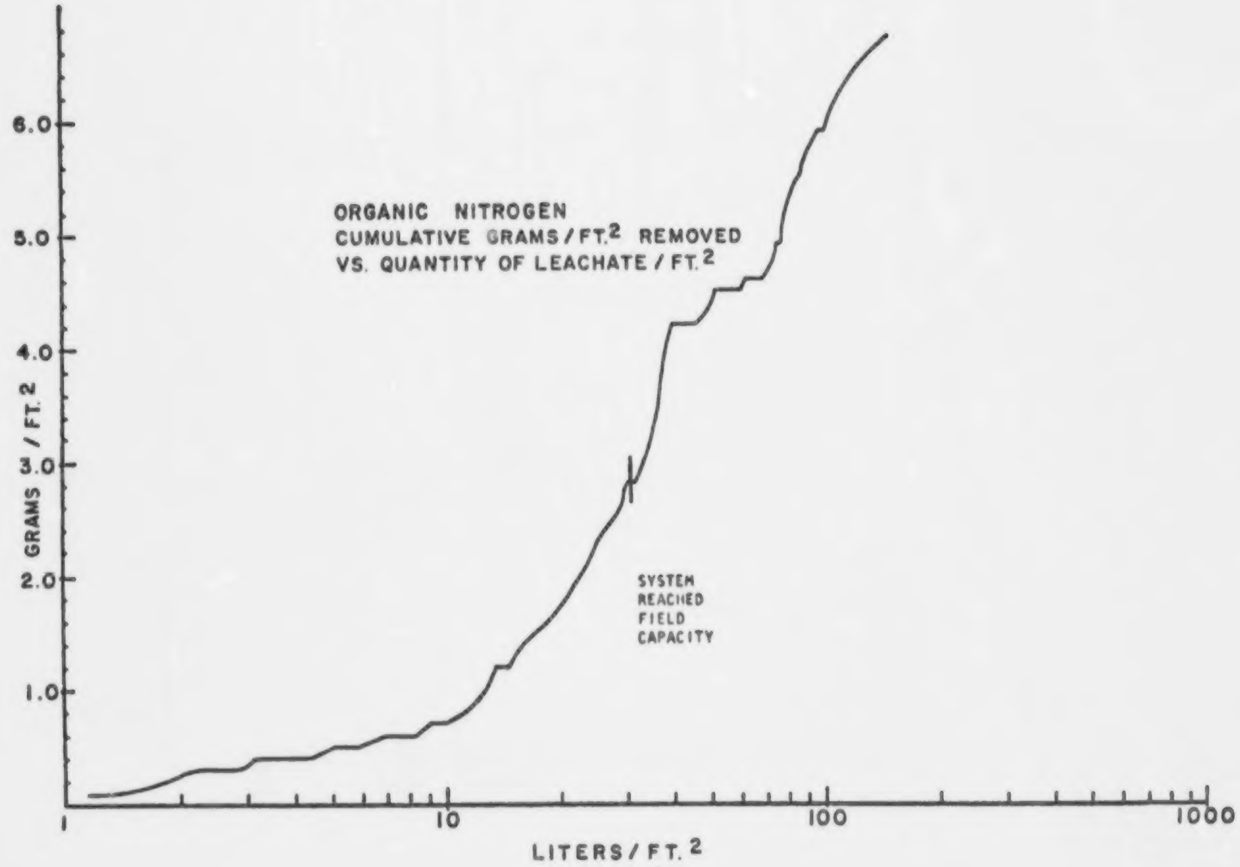

ORGANIC NITROGEN
CUMULATIVE GRAMS / FT.2 REMOVED
VS. QUANTITY OF LEACHATE / FT.2
GRAMS / FT.2
6.0
5.0
4.0
3.0
2.0
1.0
SYSTEM
REACHED
FIELD
CAPACITY
1
10
100
1000
LITERS / FT.2

FIGURE 40

FREE AMMONIA
CUMULATIVE QUANITY REMOVED WITH TIME

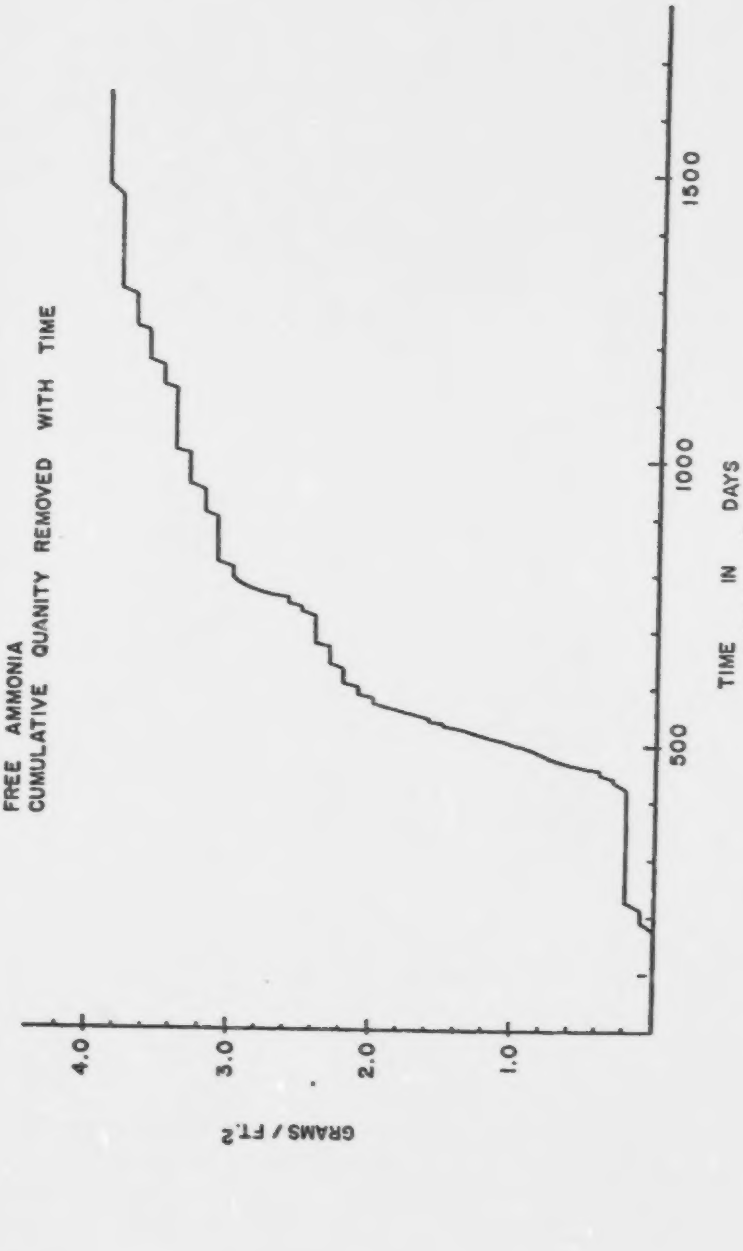
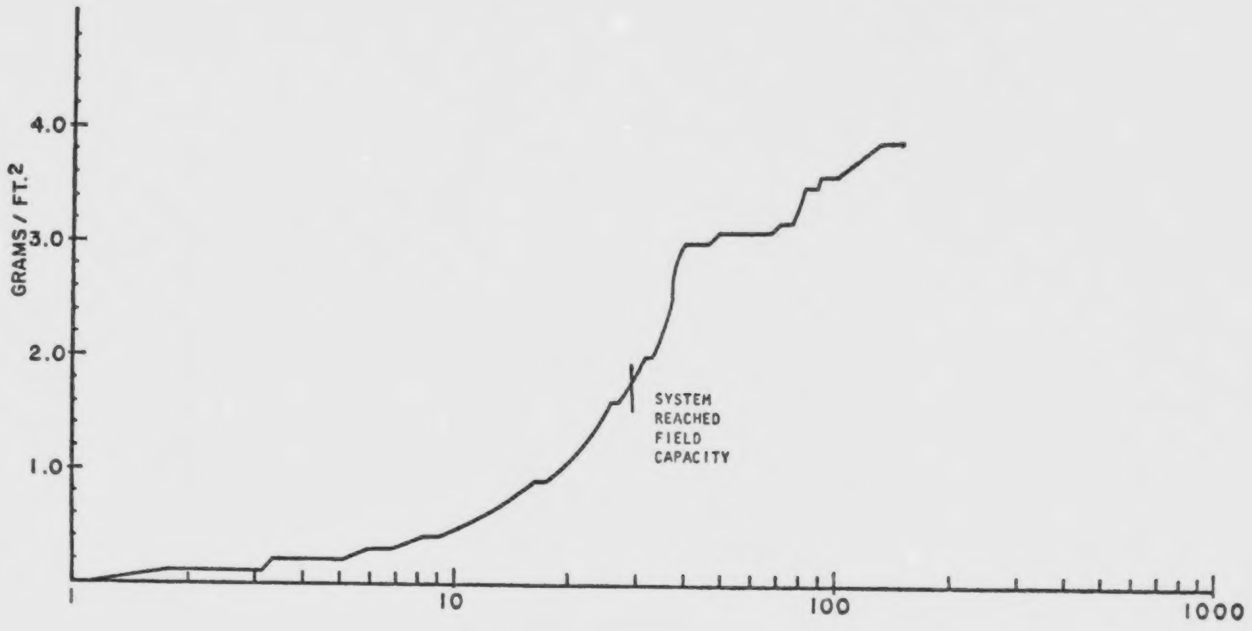


FIGURE 41

FREE AMMONIA
CUMULATIVE GRAMS / FT. ^{2} REMOVED
VS. QUANTITY OF LEACHATE / FT. ^{2}



LITERS / FT. ^{2}
FIGURE 42

Lysimeter Hardness Concentration

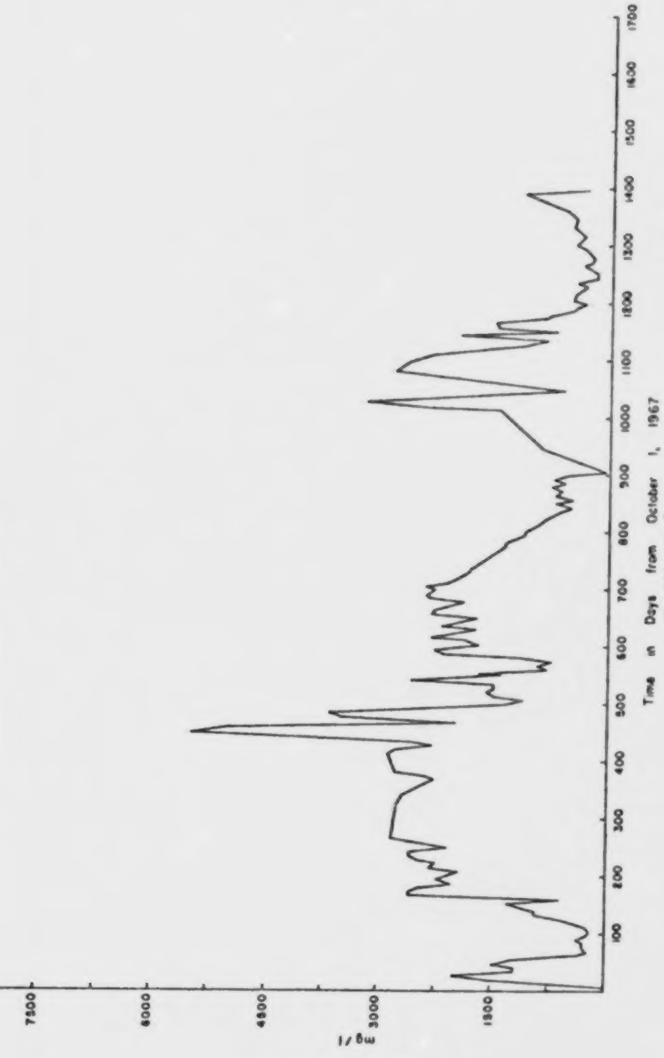


FIGURE 43

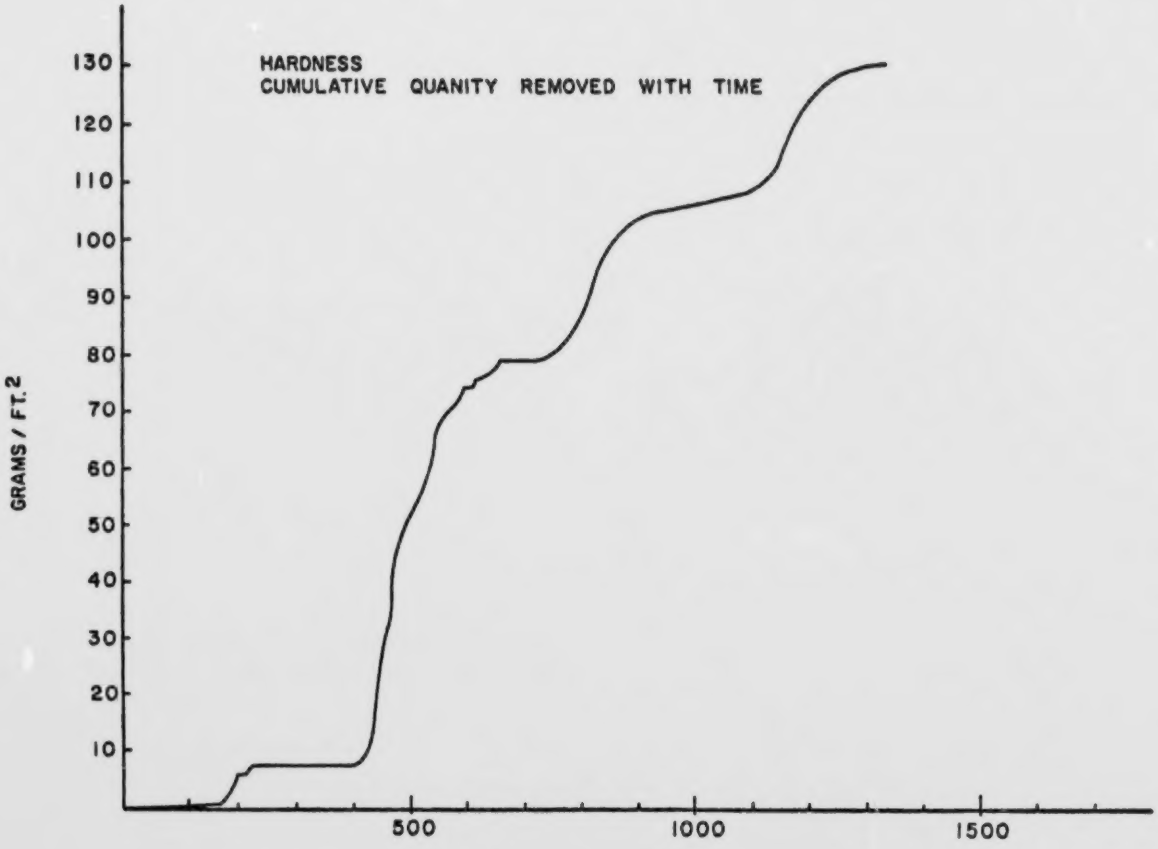
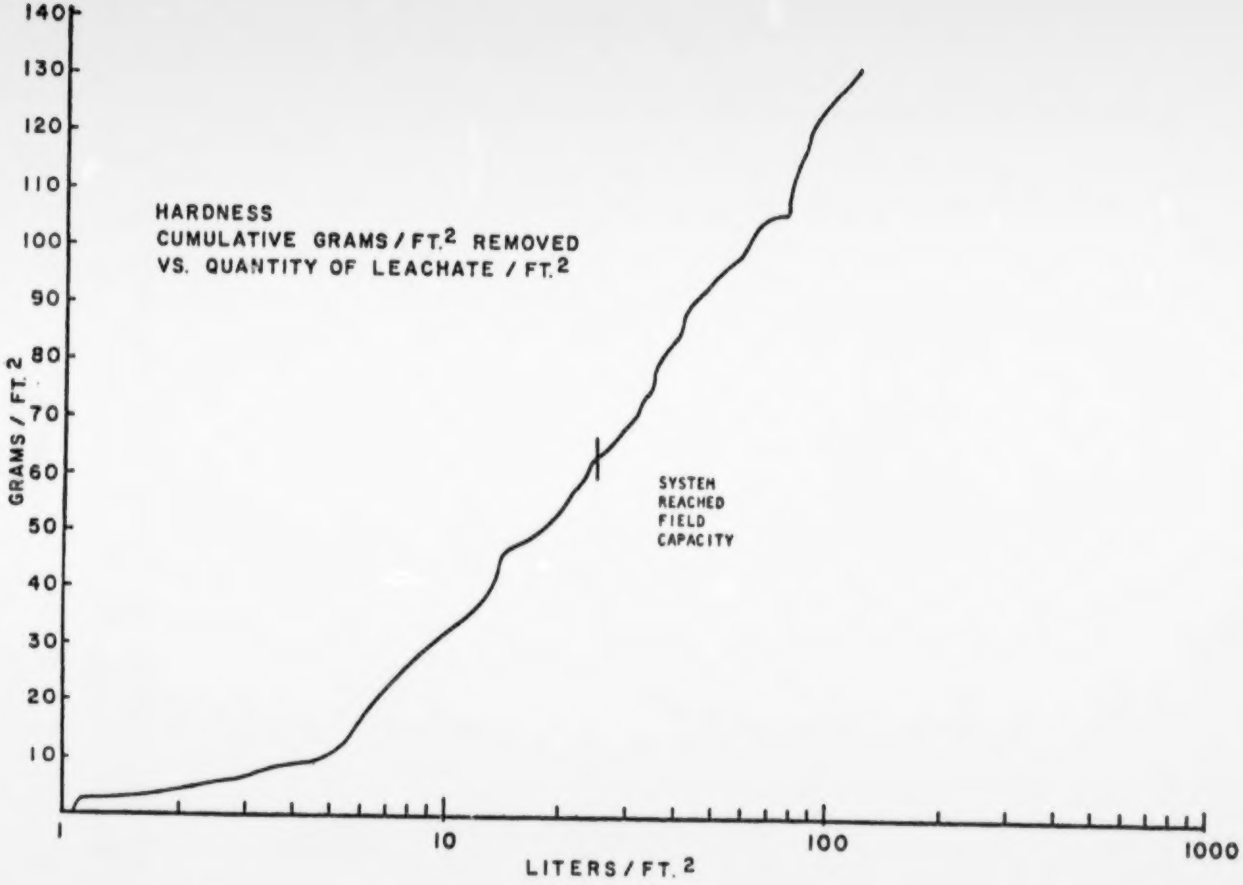
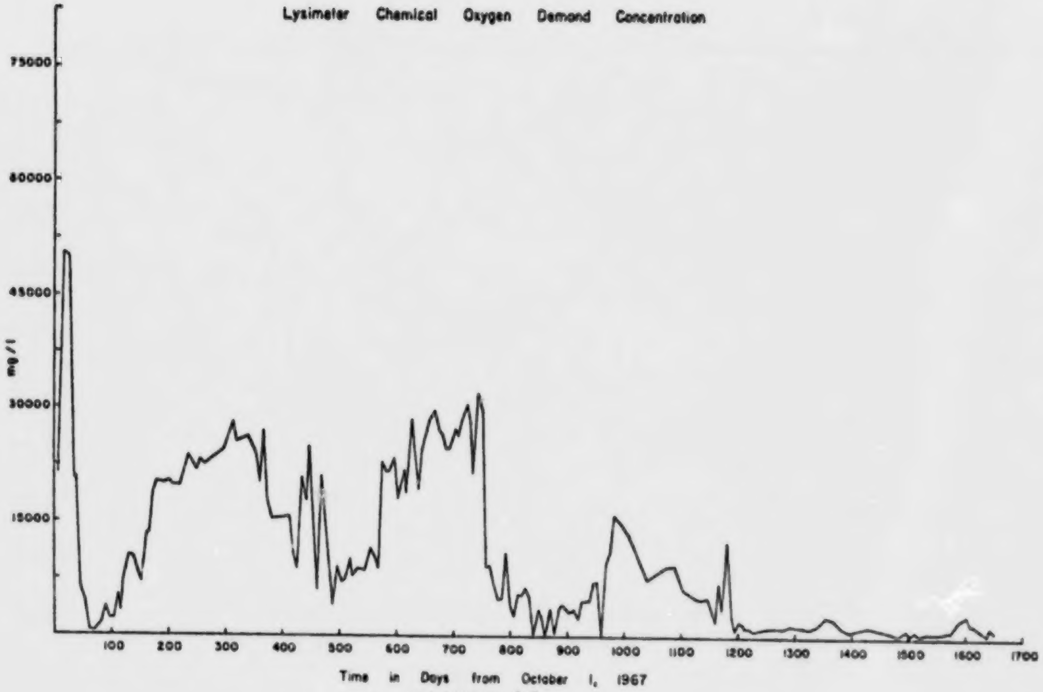

HARDNESS
CUMULATIVE QUANITY REMOVED WITH TIME
GRAMS / FT.2
130
120
110
100
90
80
70
60
50
40
30
20
10
500
1000
1500
TIME IN DAYS

FIGURE 44



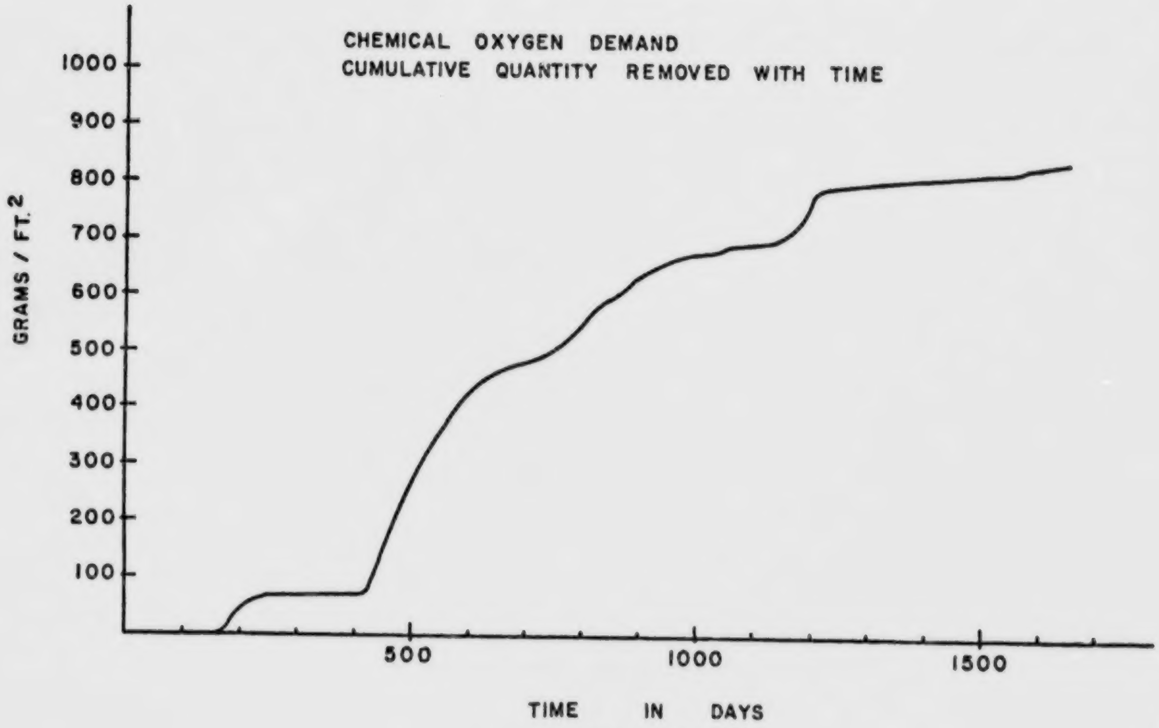
HARDNESS
CUMULATIVE GRAMS / FT.^{2} REMOVED
VS. QUANTITY OF LEACHATE / FT.^{2}

FIGURE 45



Lysimeter Chemical Oxygen Demand Concentration

FIGURE 46



CHEMICAL OXYGEN DEMAND
CUMULATIVE QUANTITY REMOVED WITH TIME

FIGURE 47

CHEMICAL OXYGEN DEMAND
CUMULATIVE GRAMS / FT.^{2} REMOVED
VS. QUANTITY OF LEACHATE / FT.^{2}

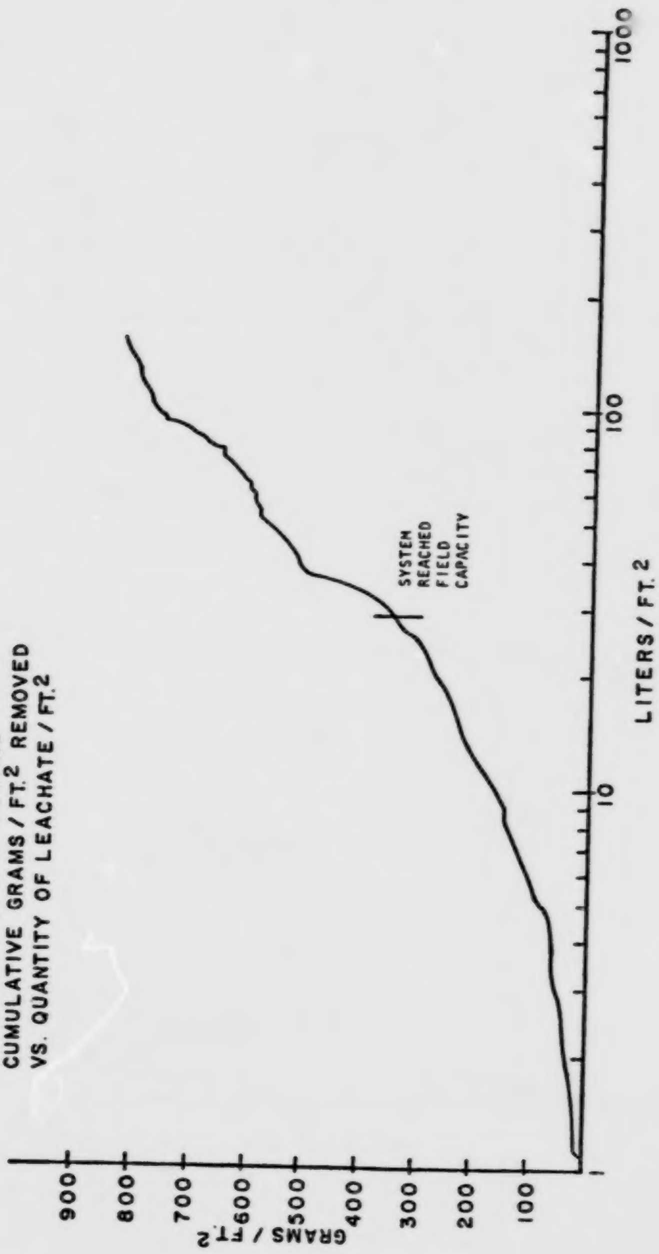
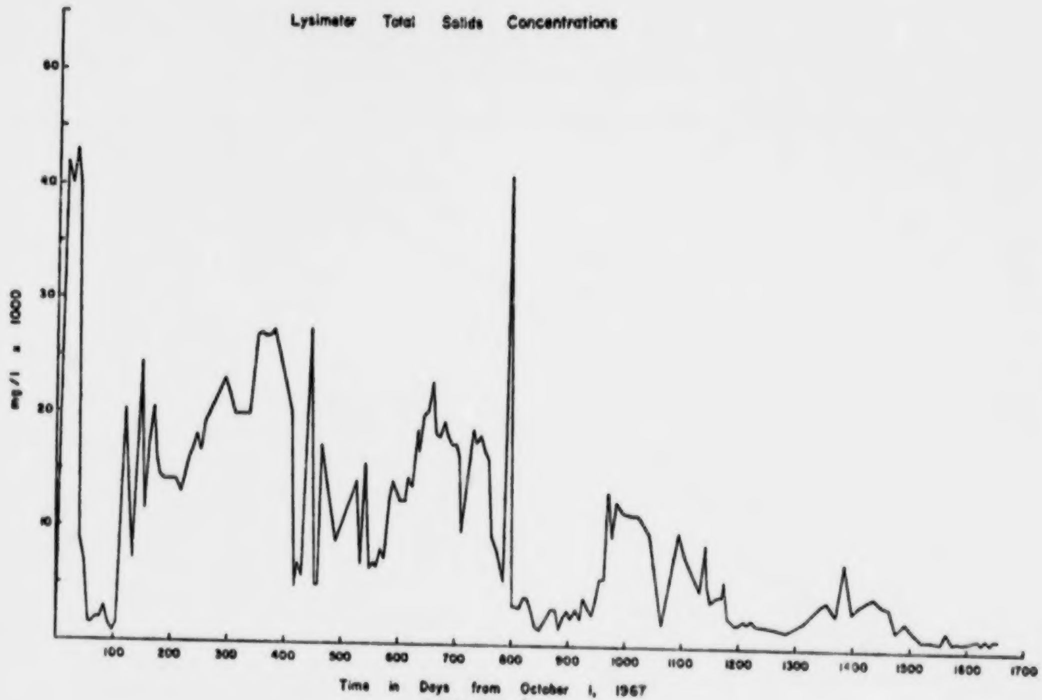


FIGURE 48



Lysimeter Total Solids Concentrations

FIGURE 49

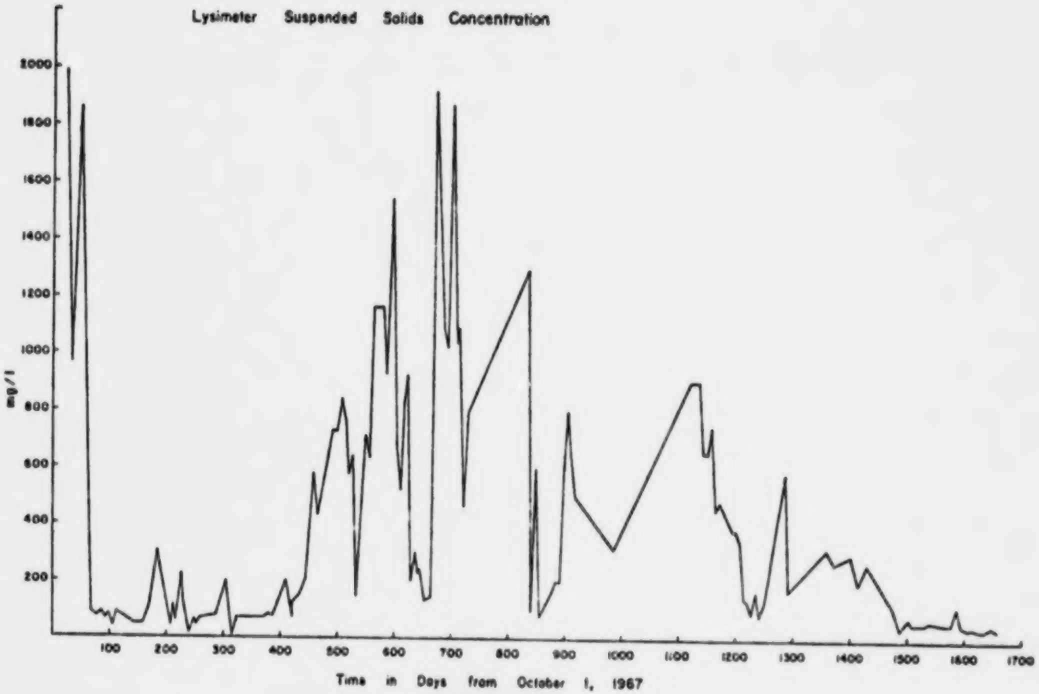

Lysimeter Suspended Solids Concentration
mg/l
2000
1800
1600
1400
1200
1000
800
600
400
200
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 50

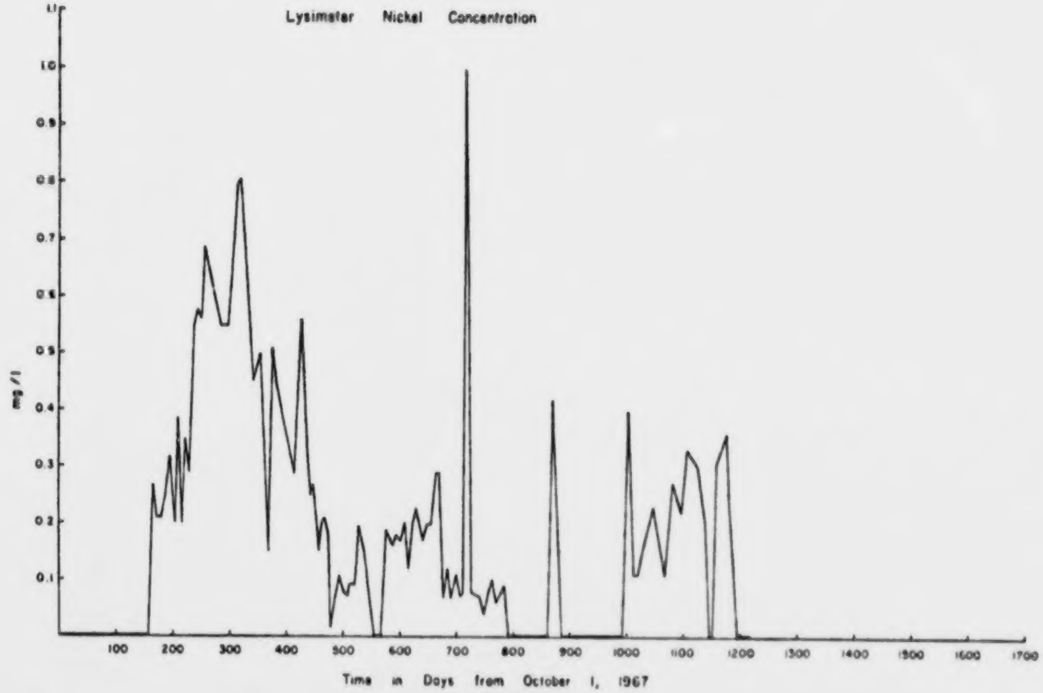

Lysimeter Nickel Concentration
mg/l
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 51

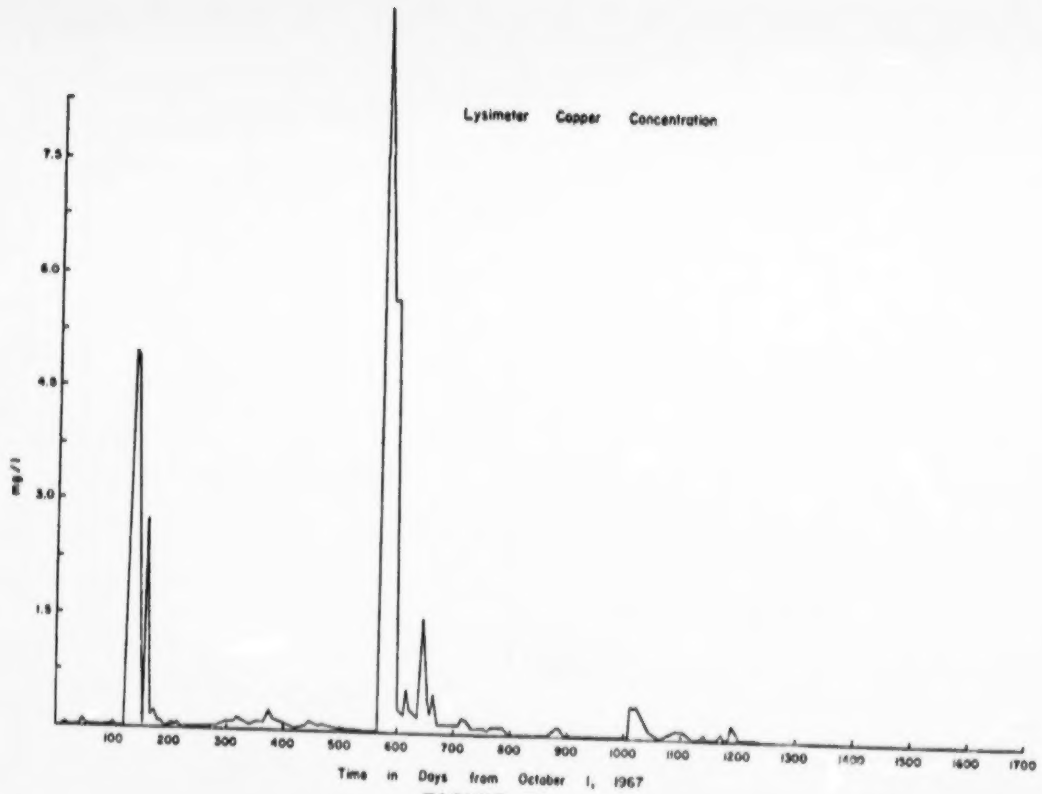
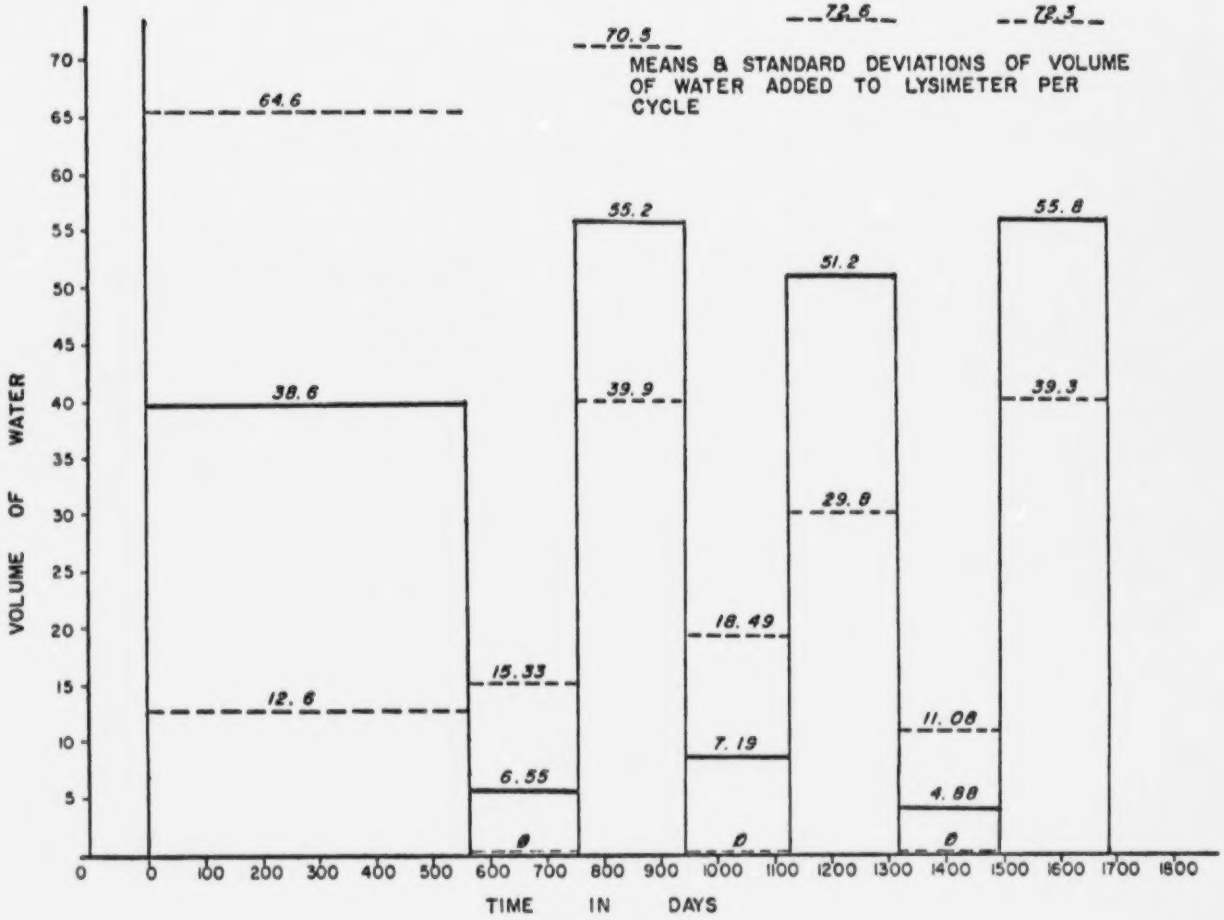
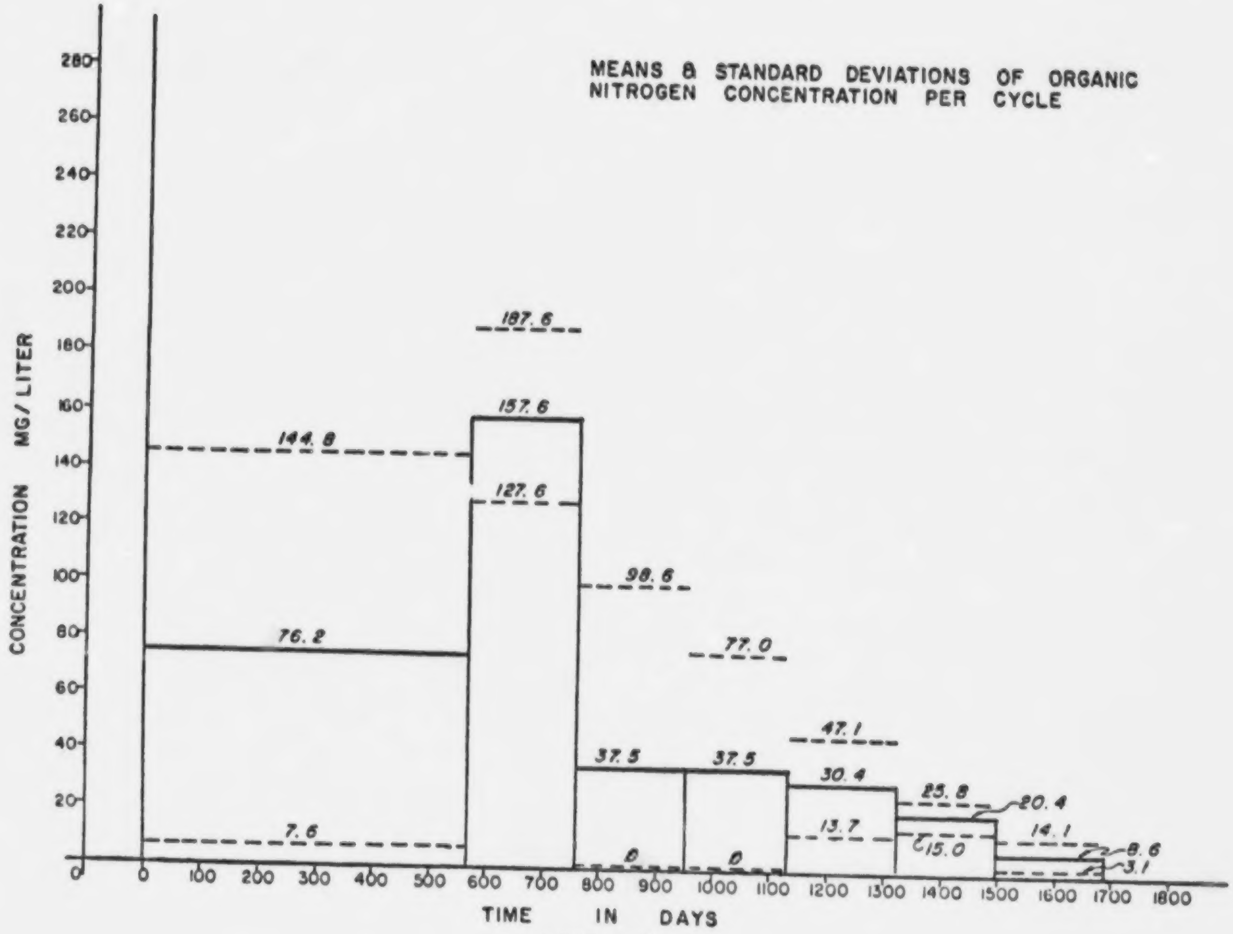

Lysimeter Copper Concentration
mg/l
7.5
6.0
4.5
3.0
1.5
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
Time in Days from October 1, 1967

FIGURE 52



MEANS & STANDARD DEVIATIONS OF VOLUME OF WATER ADDED TO LYSIMETER PER CYCLE

FIGURE 53



MEANS & STANDARD DEVIATIONS OF ORGANIC NITROGEN CONCENTRATION PER CYCLE

FIGURE 54

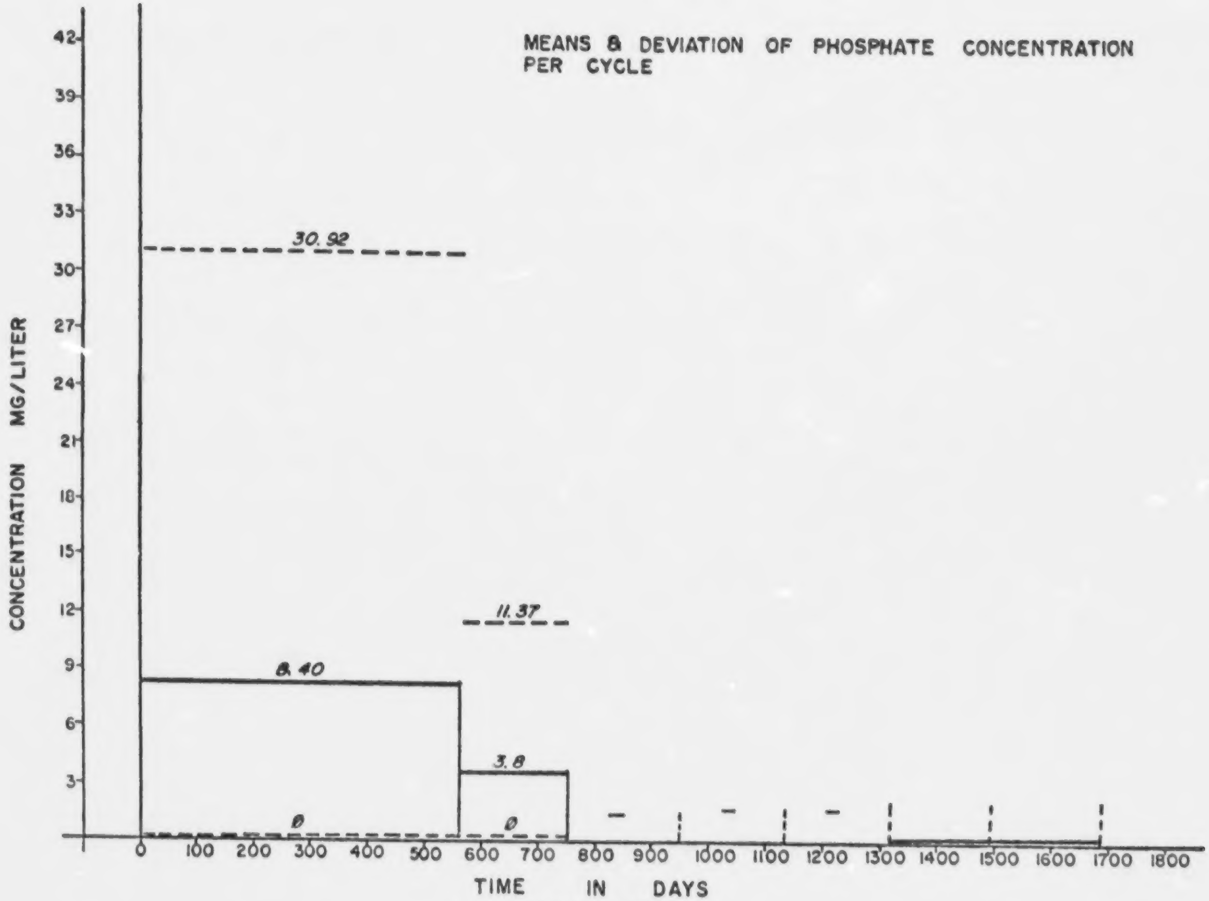
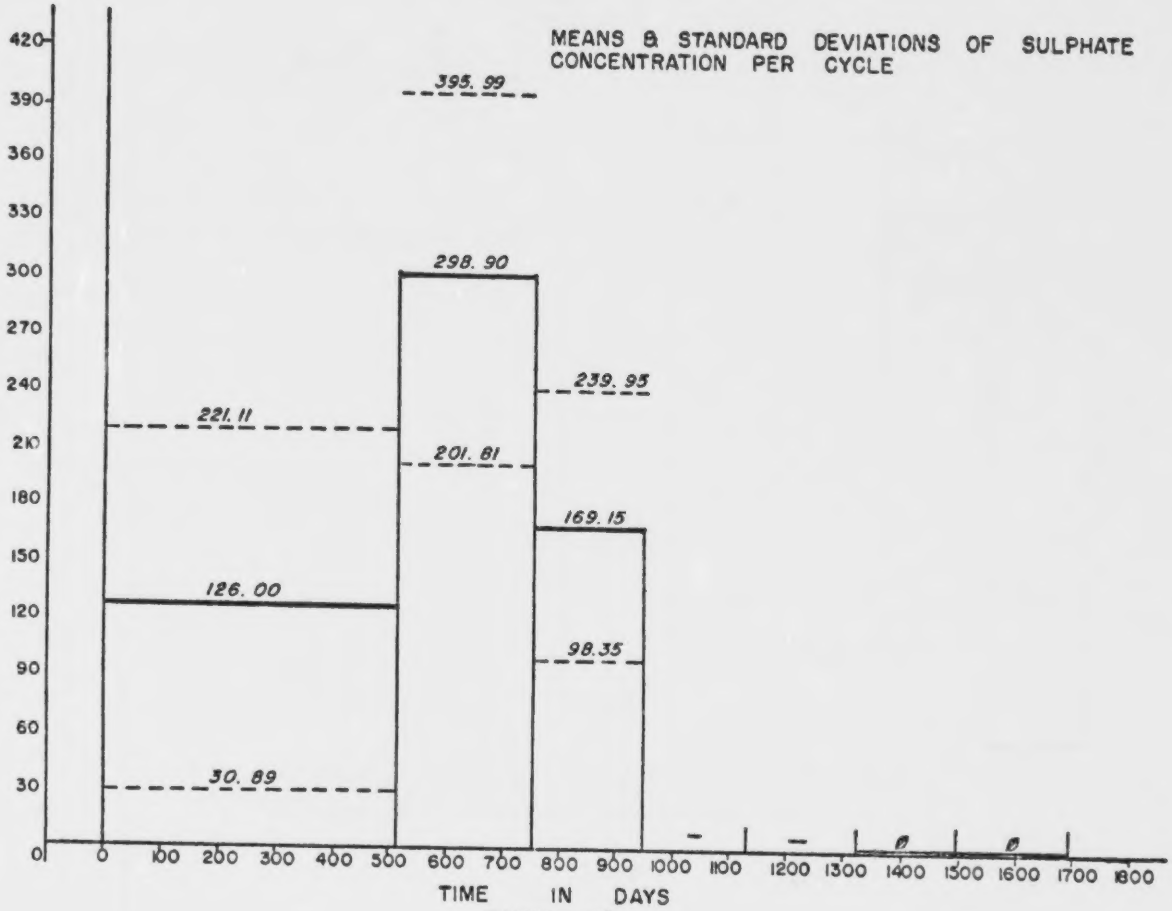
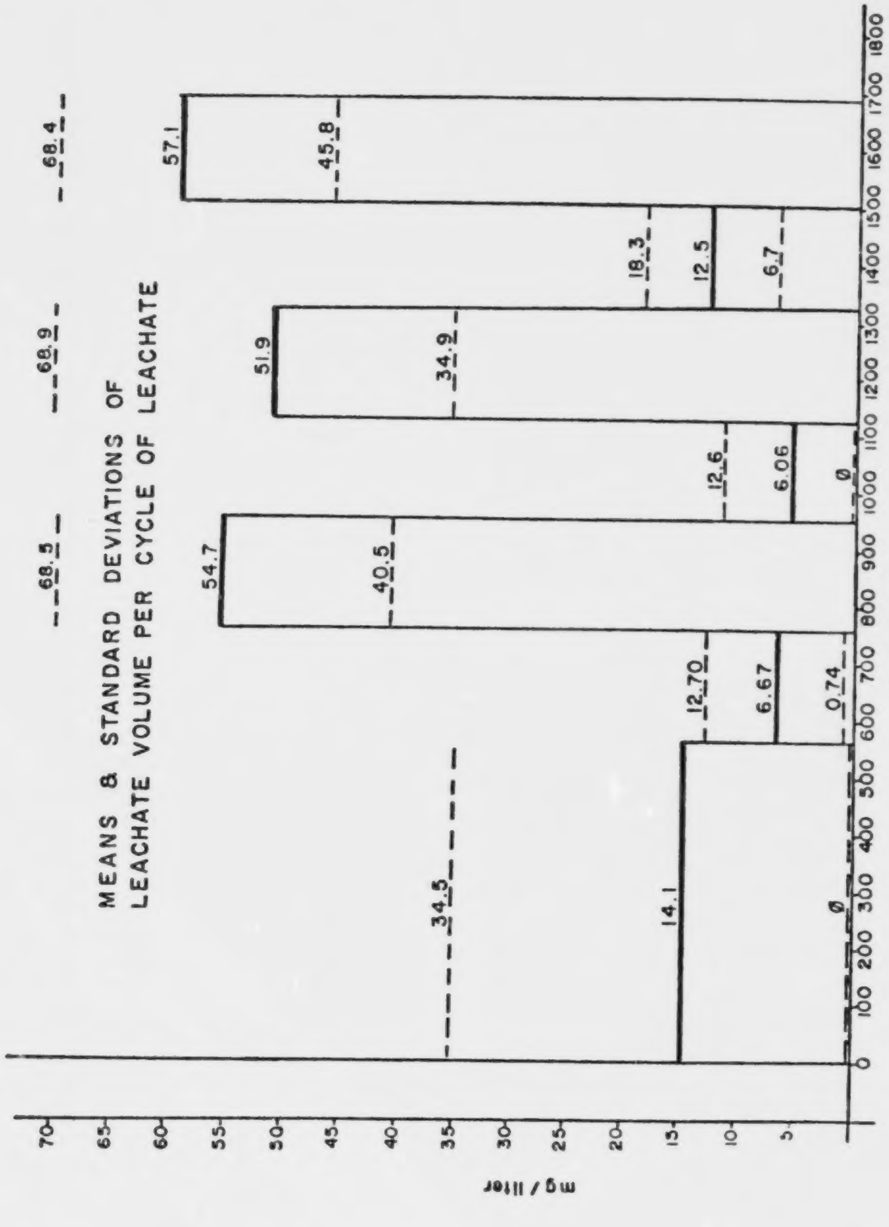

MEANS & DEVIATION OF PHOSPHATE CONCENTRATION PER CYCLE
CONCENTRATION MG/LITER
42
39
36
33
30
27
24
21
18
15
12
9
6
3
30.92
11.37
8.40
3.8
0
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
TIME IN DAYS

FIGURE 55



MEANS & STANDARD DEVIATIONS OF SULPHATE CONCENTRATION PER CYCLE

FIGURE 56



MEANS & STANDARD DEVIATIONS OF LEACHATE VOLUME PER CYCLE OF LEACHATE

FIGURE 57

MEANS & STANDARD DEVIATIONS OF IRON CONCENTRATION PER CYCLE OF LEACHATE

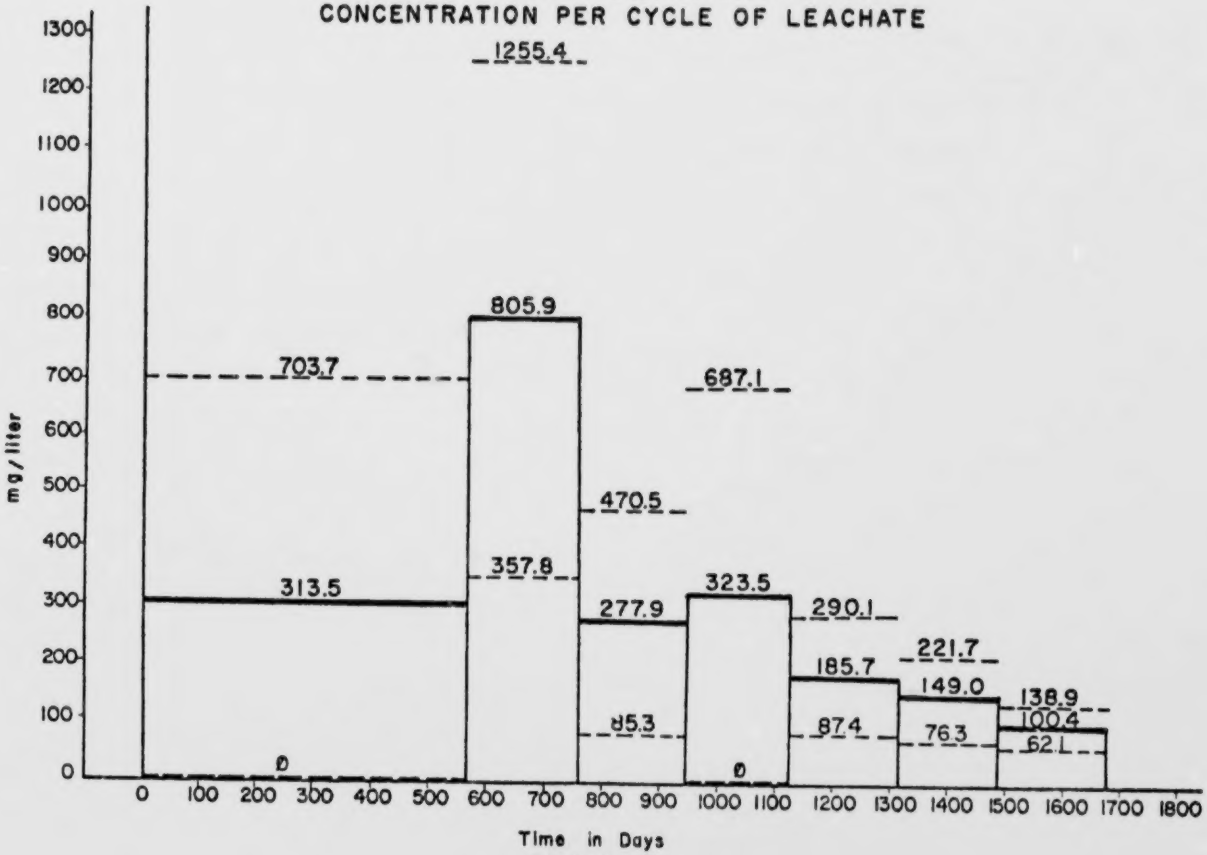


FIGURE 58

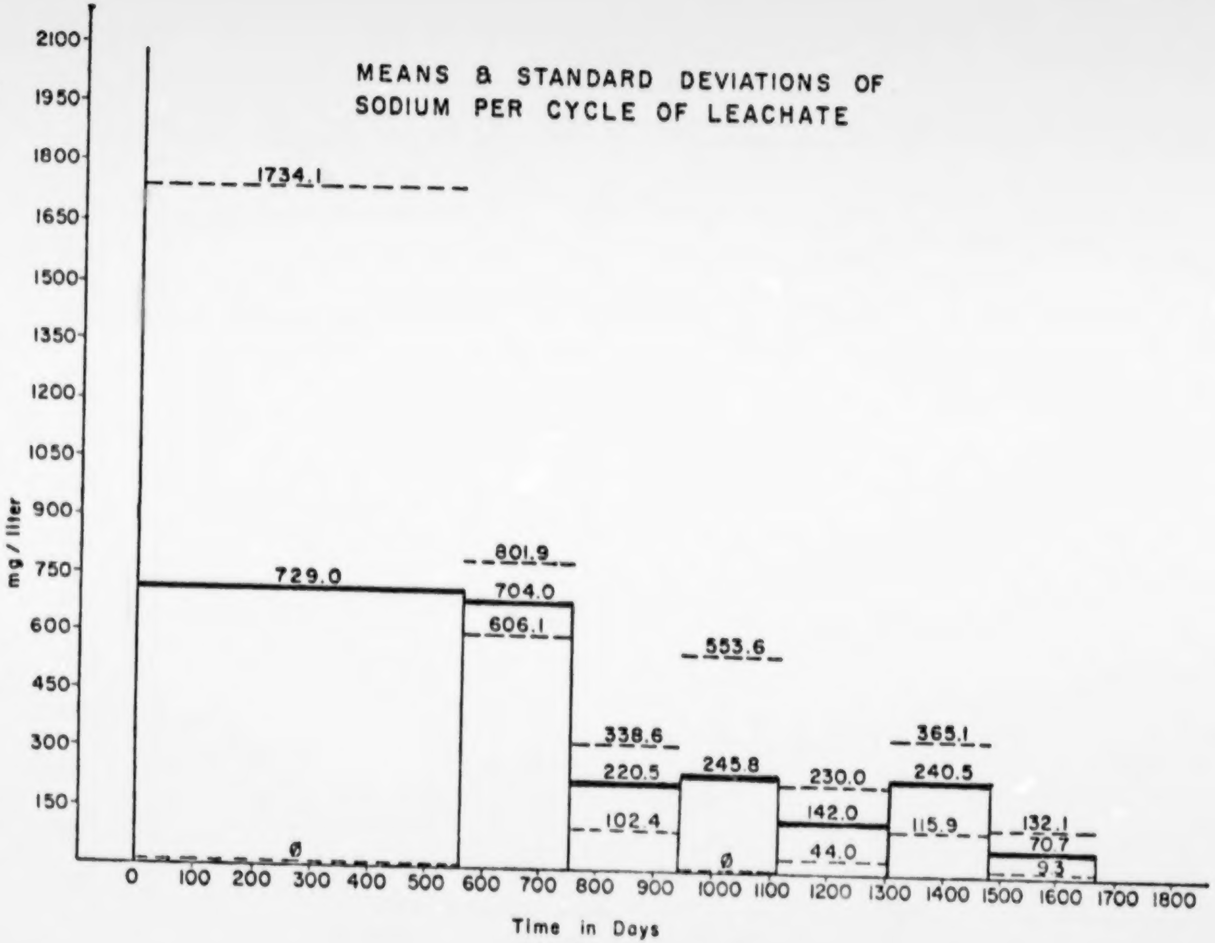
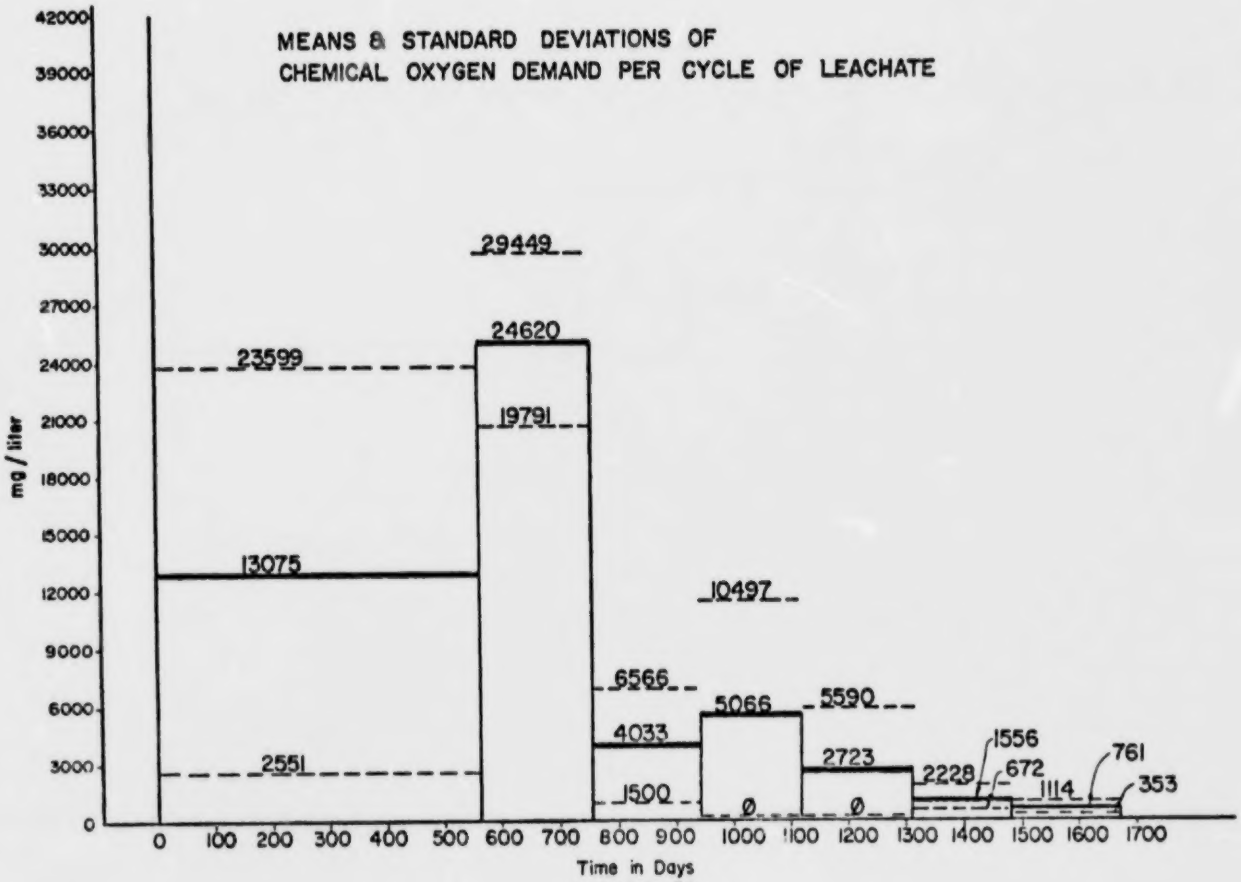

MEANS & STANDARD DEVIATIONS OF
SODIUM PER CYCLE OF LEACHATE
mg / liter
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
300
150
1734.1
729.0
Ø
801.9
704.0
606.1
553.6
338.6
220.5
102.4
245.8
Ø
230.0
142.0
44.0
365.1
240.5
115.9
132.1
70.7
9.3
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Time in Days

FIGURE 59



MEANS & STANDARD DEVIATIONS OF
CHEMICAL OXYGEN DEMAND PER CYCLE OF LEACHATE

FIGURE 60

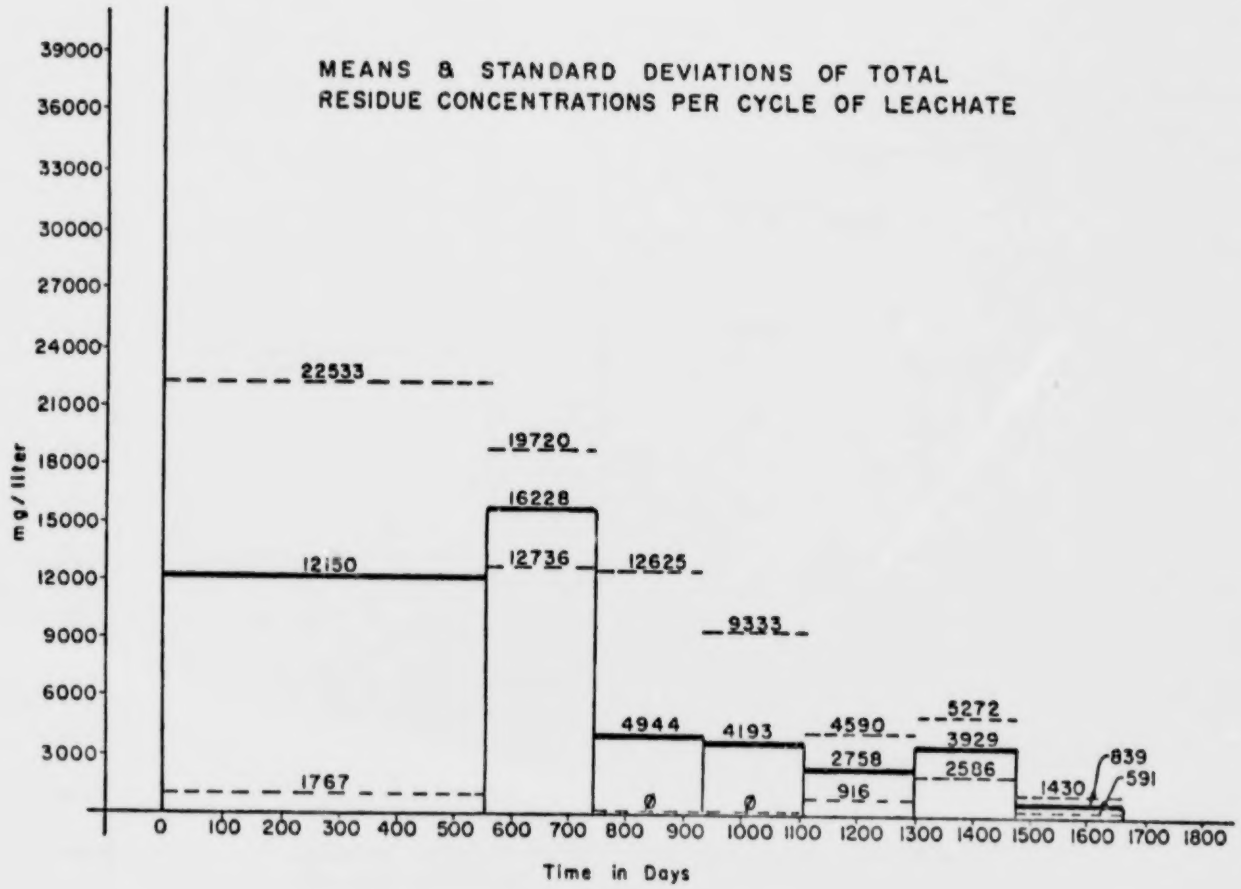

MEANS & STANDARD DEVIATIONS OF TOTAL RESIDUE CONCENTRATIONS PER CYCLE OF LEACHATE
mg/liter
39000
36000
33000
30000
27000
24000
21000
18000
15000
12000
9000
6000
3000
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Time in Days
22533
12150
1767
19720
16228
12736
12625
4944
0
9333
4193
0
4590
2758
916
5272
3929
2586
1430
839
591

FIGURE 61

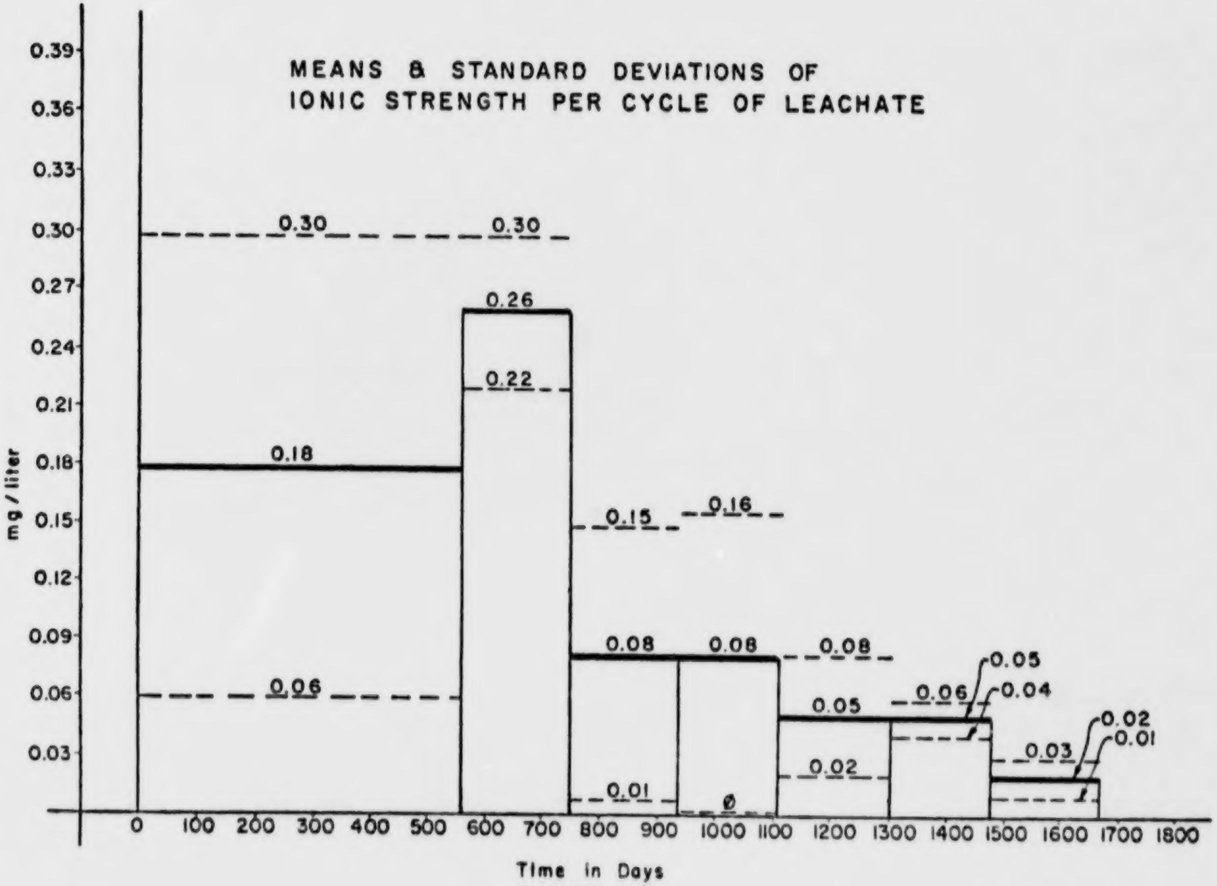

MEANS & STANDARD DEVIATIONS OF IONIC STRENGTH PER CYCLE OF LEACHATE

FIGURE 62

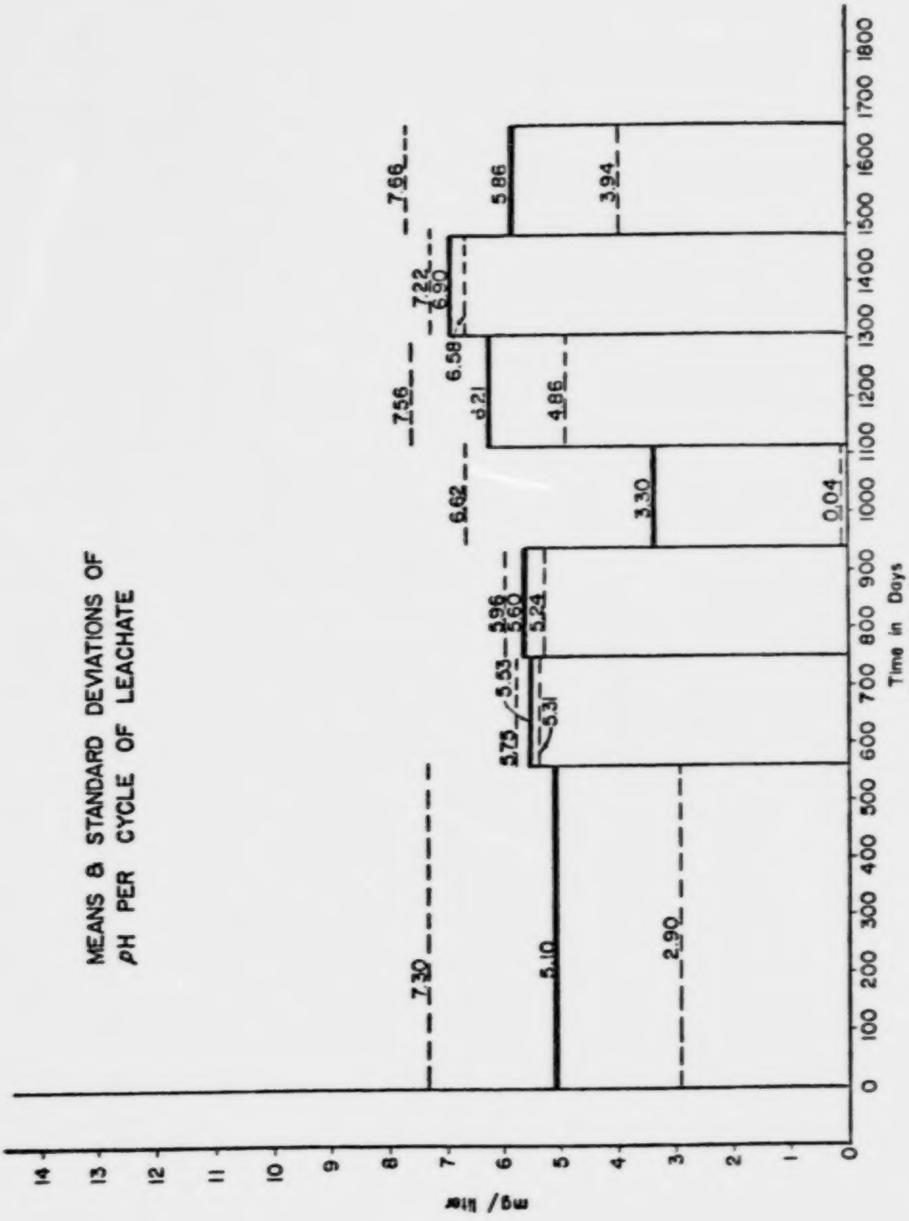

MEANS & STANDARD DEVIATIONS OF
pH PER CYCLE OF LEACHATE
mg / liter
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Time in Days
7.30
5.10
2.90
5.75
5.53
5.31
5.96
5.60
5.24
6.62
3.30
0.04
7.56
6.21
4.86
7.22
6.90
6.58
7.66
5.86
3.94

FIGURE 63

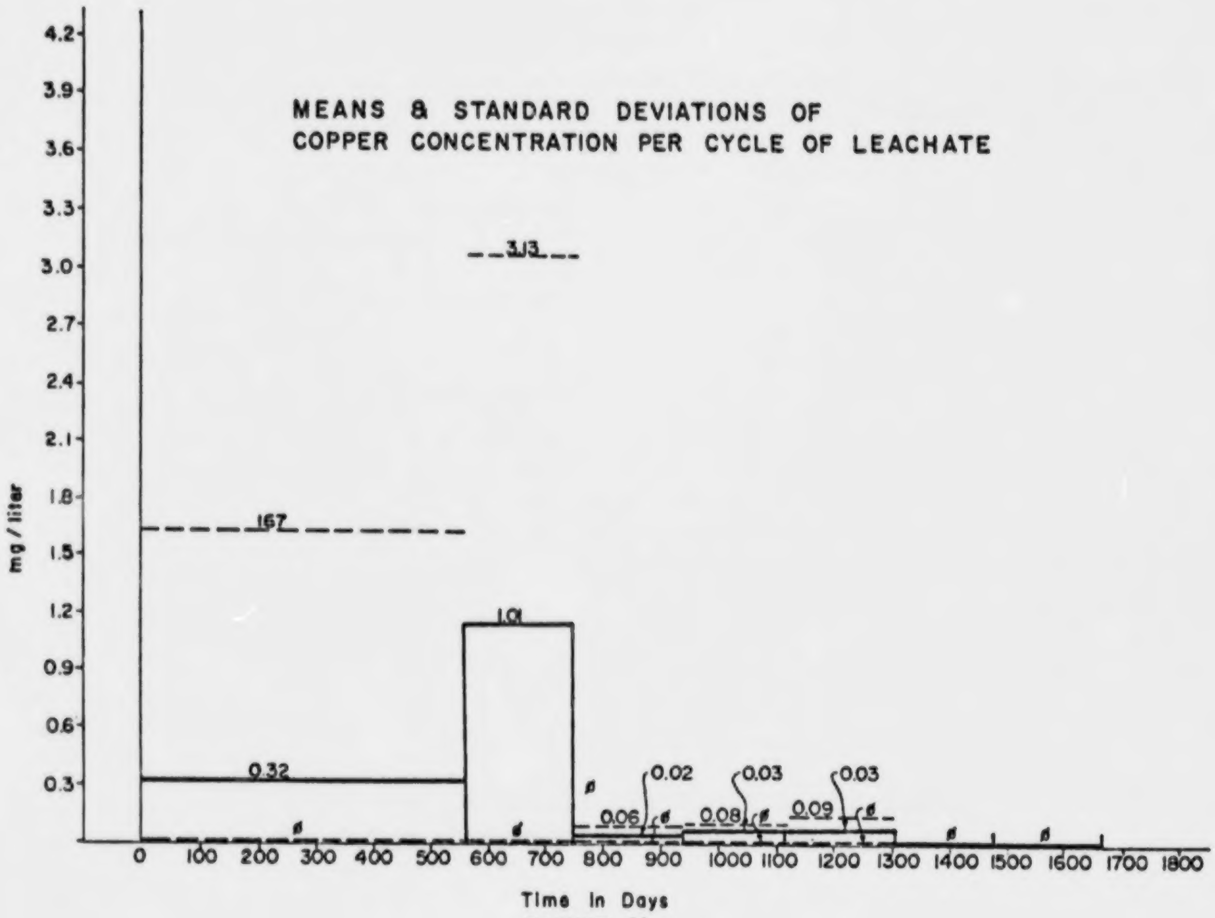

MEANS & STANDARD DEVIATIONS OF
COPPER CONCENTRATION PER CYCLE OF LEACHATE
mg / liter
4.2
3.9
3.6
3.3
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
3.13
1.67
1.01
0.32
0
0
0
0.06
0.02
0
0.08
0.03
0
0.09
0.03
0
0
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Time In Days

FIGURE 64

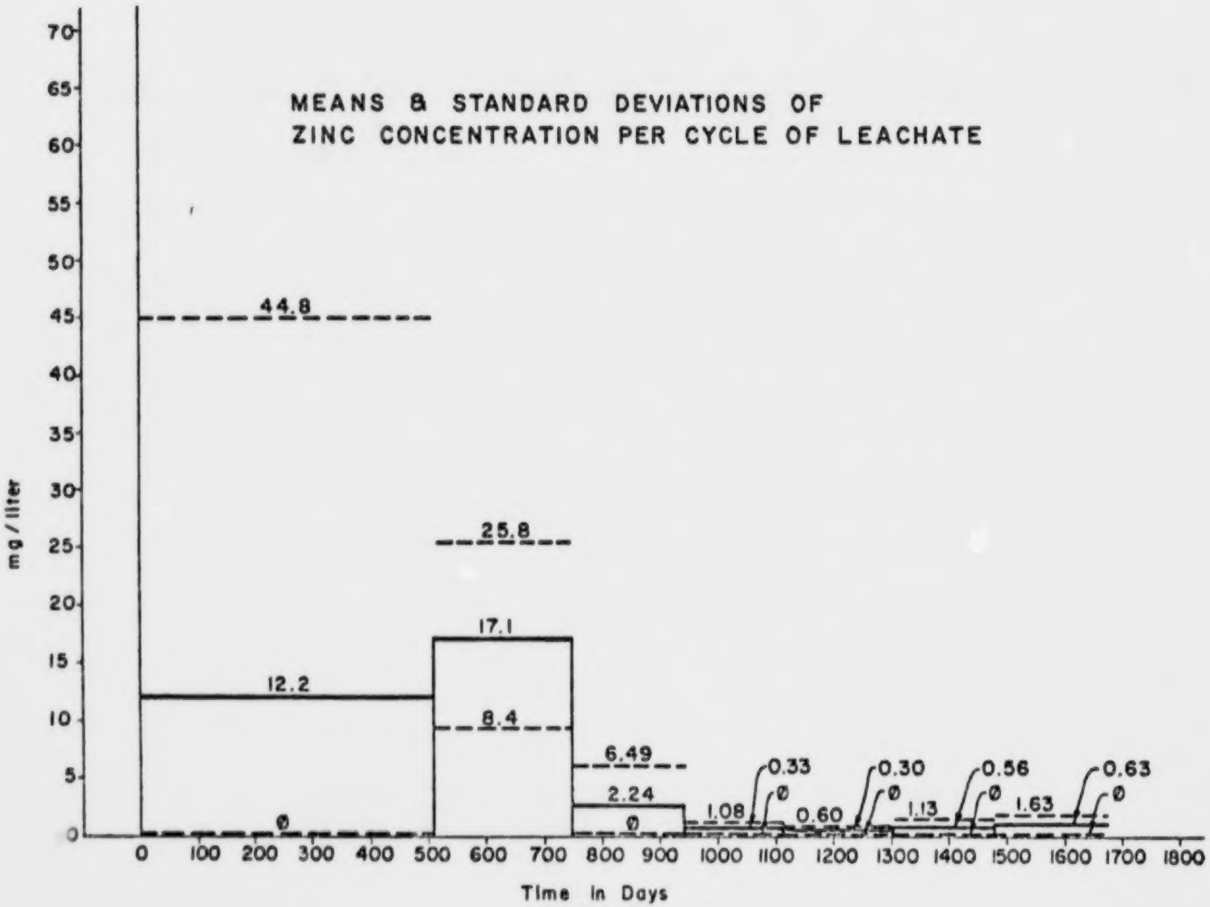
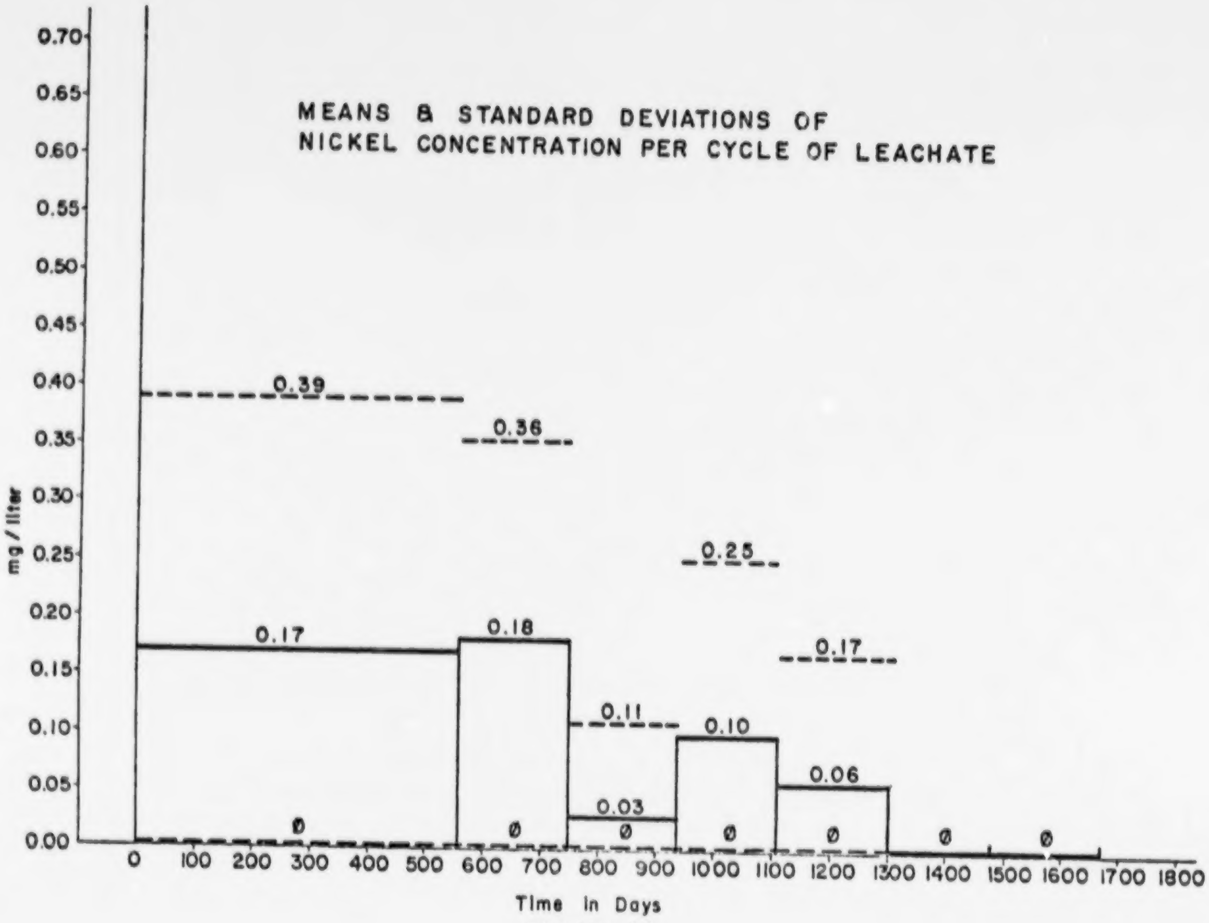

MEANS & STANDARD DEVIATIONS OF
ZINC CONCENTRATION PER CYCLE OF LEACHATE
mg / liter
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Time in Days
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
44.8
12.2
0
25.8
17.1
8.4
6.49
2.24
0
1.08
0.33
0
0.60
0.30
0
1.13
0.56
0
1.63
0.63
0

FIGURE 65



MEANS & STANDARD DEVIATIONS OF
NICKEL CONCENTRATION PER CYCLE OF LEACHATE

FIGURE 66

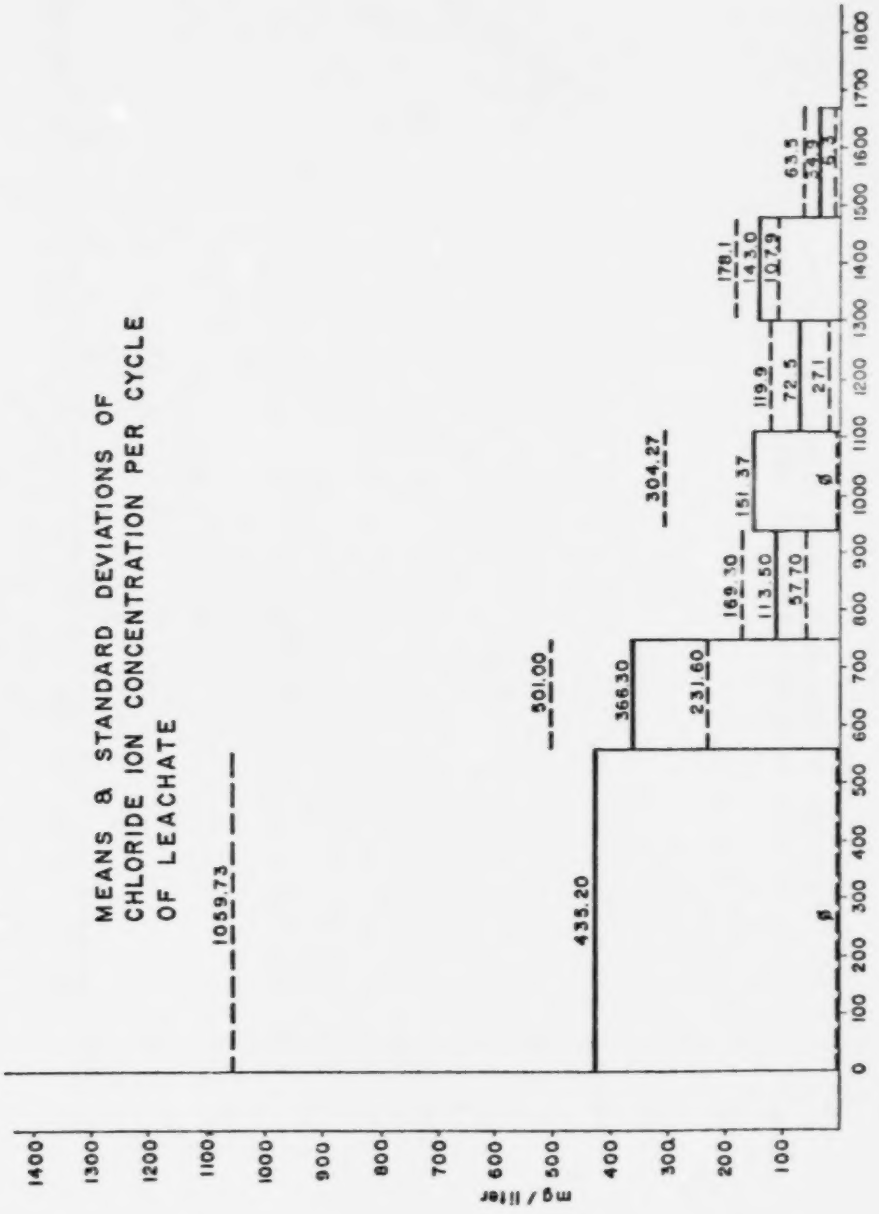

MEANS & STANDARD DEVIATIONS OF CHLORIDE ION CONCENTRATION PER CYCLE OF LEACHATE
mg / liter
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
Time in Days
1059.73
435.20
ø
501.00
366.30
231.60
304.27
169.30
113.50
57.70
151.37
ø
119.9
72.5
27.1
178.1
143.0
107.9
63.5
33.3
5.2

FIGURE 67

MEANS & STANDARD DEVIATIONS OF FREE AMMONIA CONCENTRATION PER CYCLE OF LEACHATE

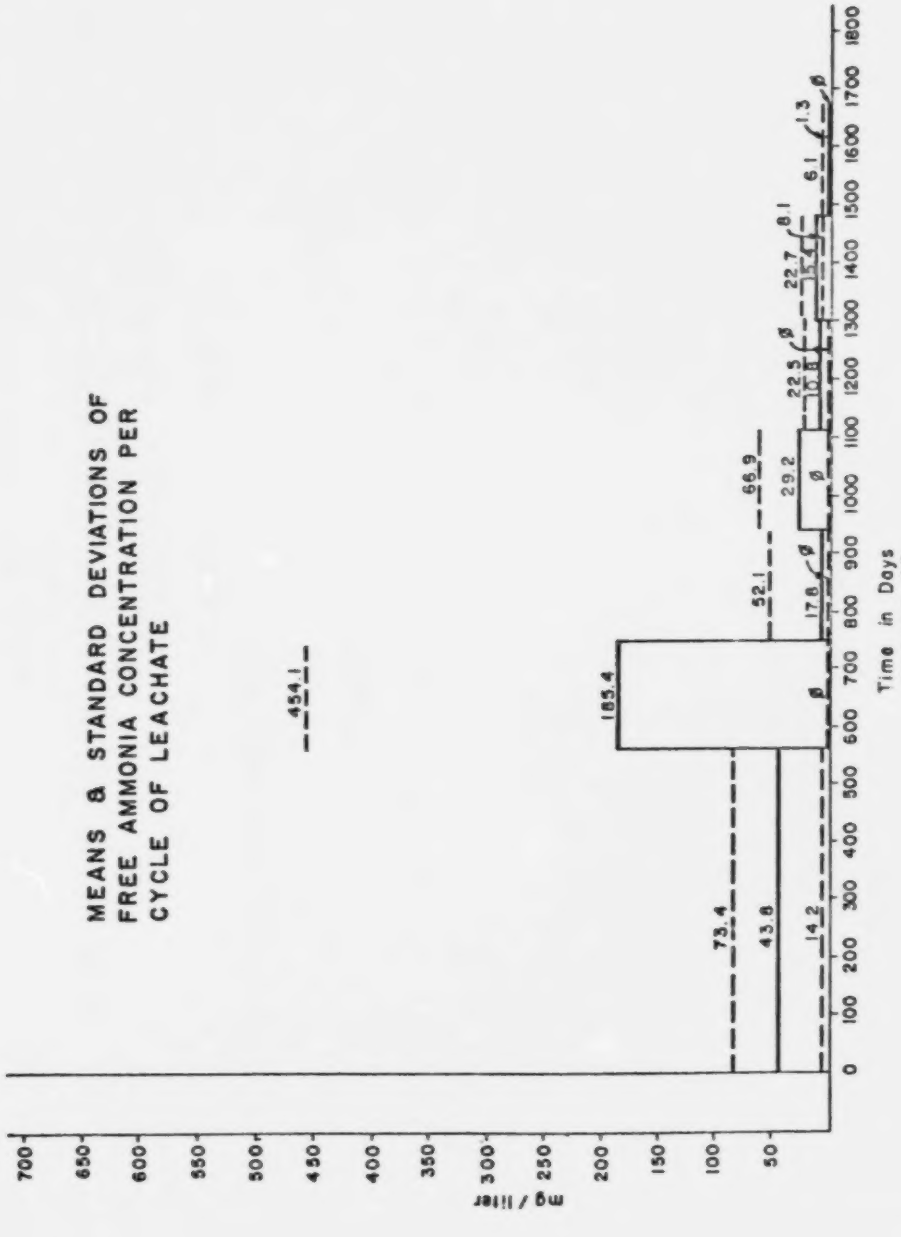
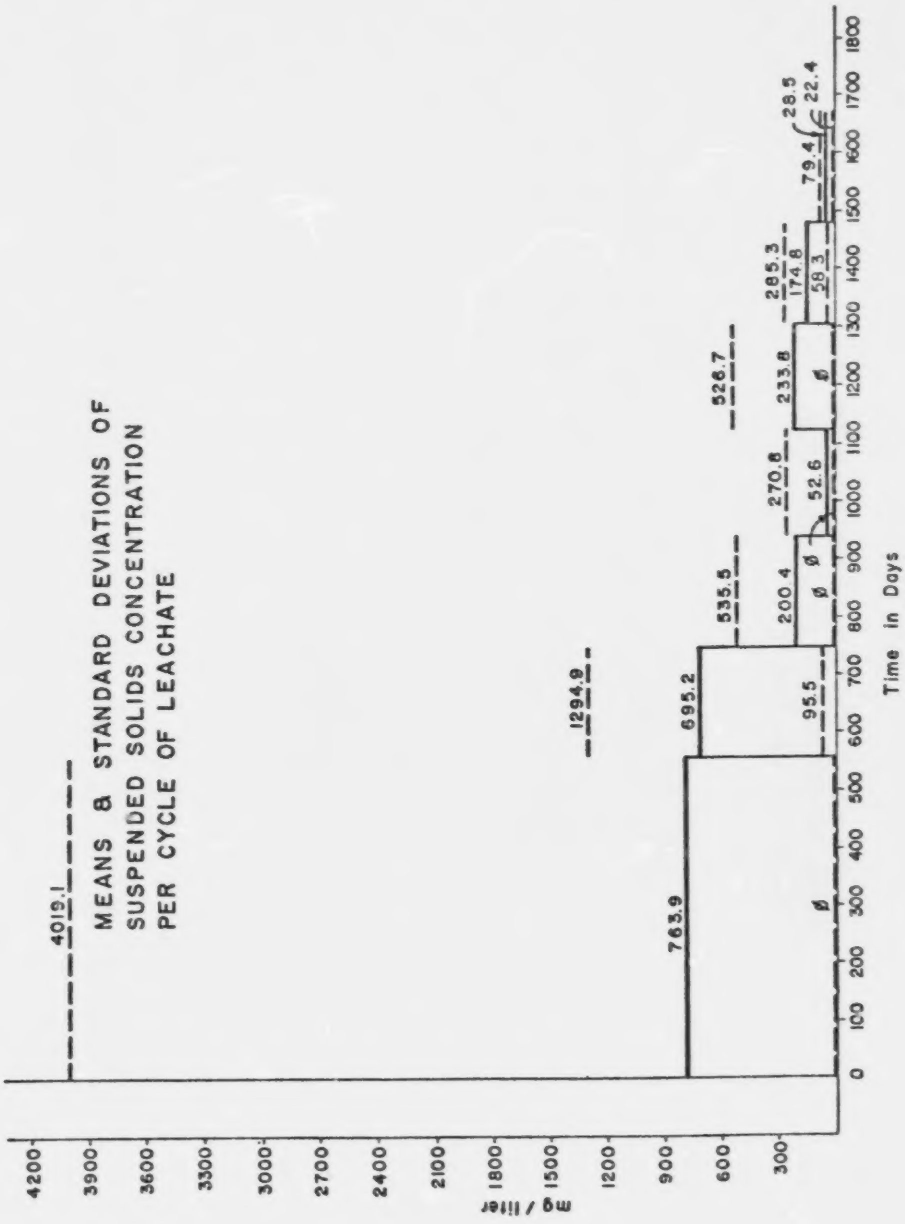


FIGURE 68



Time in Days
FIGURE 69

TABLE 13

LEACHATE CHEMICAL COMPOSITION DATA CORRELATION

From Start of Test to Day 560*

	VA	Lea	Fe	Zn	Ni	Cu	pH	Hard	PO_4	SO_4	Cl	Na	TS	SS	AN	ON	COD	Alk	IS	Day
VA	+	+																		
Lea	+	+																		
Fe	-	+	+																	
Zn	+	+	+	+																
Ni	+	-	-	-	+															
Cu	-	-	-	-	-	+														
pH	+	-	-	-	+	-	+													
Hard	-	+	+	+	+	-	+	+												
PO_4	-	-	-	-	-	-	-	-	+											
SO_4	-	-	+	-	+	-	+	+	-	+										
Cl	+	-	-	-	+	-	+	+	-	+	+									
Na	-	-	-	-	+	-	+	+	-	-	-	+								
TS	-	-	+	-	+	-	-	-	-	+	-	-	+							
SS	-	-	-	-	-	-	-	-	+	-	-	-	-	+						
AN	-	+	-	-	-	-	+	+	+	+	-	-	-	-	+					
ON	-	-	-	-	-	-	+	+	+	+	+	-	-	+	+	+				
COD	-	-	-	-	+	-	+	+	+	+	+	+	+	+	+	+	+			
Alk	-	-	-	-	+	-	+	+	+	+	+	+	-	+	+	+	+	+		
IS	-	-	+	-	+	-	+	+	+	+	+	+	+	-	+	+	+	+	+	
Day	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+

VA - Volume Added
Lea - Leachate
FE - Iron
Zn - Zinc
Ni - Nickel
Cu - Copper
Hard - Hardness
PO_4 - Phosphate
SO_4 - Sulfate
Cl - Chloride
Na - Sodium
TS - Total Solids
SS - Suspended Solids
AN - Ammonia Nitrogen
ON - Organic Nitrogen
COD - Chemical Oxygen Demand
Alk - Alkalinity
IS - Ionic Strength
+ - Linear Correlation
- - No Linear Correlation

*Entire system reached field capacity.

TABLE 14
LEACHATE CHEMICAL COMPOSITION DATA CORRELATION
From Day 560* to Day 745

	Va	Lea	Fe	Zn	Ni	Cu	pH	Hard	PO_4	SO_4	Cl	Na	TS	SS	AN	ON	COD	Alk	IS	Day
VA	+																			
Lea	-	+																		
Fe	+	-	+																	
Zn	+	-	-	+																
Ni	-	-	-	-	+															
Cu	-	+	+	+	-	+														
pH	+	-	-	-	-	-	+													
Hard	+	-	-	-	-	-	-	+												
PO_4	-	+	-	-	-	+	-	-	+											
SO_4	-	+	-	-	-	-	-	-	+	+										
Cl	-	-	-	-	-	-	-	-	-	-	+									
Na	+	-	-	+	-	-	+	+	-	-	-	+								
TS	-	-	-	-	-	-	-	-	-	-	-	-	+							
SS	-	-	-	-	-	-	-	-	-	-	-	-	-	+						
AN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+					
ON	-	+	-	-	-	+	-	-	+	+	-	-	-	-	-	+				
COD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+			
Alk	-	+	-	-	-	+	-	-	+	-	-	-	-	-	-	-	-	+		
IS	+	-	+	-	-	-	+	+	-	-	-	+	-	-	-	-	-	+	+	
Day	+	+	+	-	-	+	+	-	+	+	-	-	-	-	-	+	-	-	-	+

VA - Volume Added
Lea - Leachate
Fe - Iron
Zn - Zinc
Ni - Nickel
Cu - Copper
Hard - Hardness
PO_4 - Phosphate
SO_4 - Sulfate
Cl - Chloride
NA - Sodium
TS - Total Solids
SS - Suspended Solids
AN - Ammonia Nitrogen
ON - Organic Nitrogen
COD - Chemical Oxygen Demand
Alk - Alkalinity
IS - Ionic Strength
+ - Linear Correlation
- - No Linear Correlation

*Entire system reached field capacity.

TABLE 15

LEACHATE CHEMICAL COMPOSITION DATA CORRELATION

From Day 745* to Day 940

	Va	Lea	Fe	Zn	Ni	Cu	pH	Hard	PO_4	SO_4	Cl	Na	TS	SS	AN	ON	COD	Alk	IS	Day
VA	+																			
Lea	-	+																		
FE	-	-	+																	
Zn.	-	-	-	+																
Ni	-	-	-	-	+															
Cu	-	-	-	-	-	+														
pH	-	-	-	-	-	-	+													
Hard	-	-	-	-	-	-	-	+												
PO_4	-	-	-	-	-	-	-	-	+											
SO_4	-	-	-	-	-	-	-	-	-	+										
Cl	-	-	-	-	-	-	-	-	-	-	+									
Na	-	+	-	-	-	-	+	+	-	-	-	+								
TS	-	-	-	-	-	-	-	-	-	-	-	-	-							
SS	-	-	-	-	-	-	-	-	-	-	-	+	-	+						
AN	-	-	-	+	-	+	-	-	-	-	-	+	-	-	+					
ON	-	-	-	-	-	+	-	-	-	-	-	+	-	-	+	+				
COD	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+			
Alk	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	
Day	-	-	-	-	-	-	+	+	-	-	-	+	-	-	-	-	+	-	+	+

VA - Volume Added
Lea - Leachate
Fe - Iron
Zn - Zinc
Ni - Nickel
Cu - Copper
Hard - Hardness
PO_4 - Phosphate
SO_4 - Sulfate
Cl - Chloride
NA - Sodium
TS - Total Solids
SS - Suspended Solids
AN - Ammonia Nitrogen
ON - Organic Nitrogen
COD - Chemical Oxygen Demand
Alk - Alkalinity
IS - Ionic Strength
+ - Linear Correlation
- - No Linear Correlation

*Entire system reached field capacity.

TABLE 16

LEACHATE CHEMICAL COMPOSITION DATA CORRELATION

From Day 940 to Day 1120

*Entire system reached field capacity at 560 days

	VA	Lea	Fe	Zn	Ni	Cu	pH	Hard	PO_4	SO_4	Cl	Na	TS	SS	AN	ON	COD	Alk	IS	Day
VA	+																			
Lea	-	+																		
Fe	-	+	+																	
Zn	-	-	-	+																
Ni	-	-	-	+	+															
Cu	-	-	-	+	+	+														
pH	-	+	+	-	+	+	+													
Hard	-	-	-	+	+	+	+	+												
PO_4	-	-	-	-	-	-	-	-	+											
SO_4	-	-	-	-	-	-	-	-	-	+										
Cl	-	+	+	+	+	+	+	+	-	-	+									
Na	-	+	+	+	+	+	+	+	-	-	+	+								
TS	-	-	-	-	-	-	-	-	-	-	-	-	+							
SS	-	-	-	-	-	-	-	-	-	-	-	-	-	+						
AN	-	-	+	+	+	+	+	+	-	-	+	+	-	-	+					
ON	-	+	+	-	+	-	+	-	-	-	+	+	-	-	+	+				
COD	-	+	+	-	+	-	+	-	-	-	+	+	-	-	+	+	+			
Alk	-	+	+	-	+	-	+	-	-	-	+	+	-	-	+	+	+	+		
Is	-	+	+	+	+	+	+	+	-	-	+	+	-	-	+	+	+	+	+	
Day	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+

VA - Volume Added
Lea - Leachate
Fe - Iron
Zn - Zinc
Ni - Nickel
Cu - Copper
Hard - Hardness
PO_4 - Phosphate
SO_4 - Sulfate
Cl - Chloride
Na - Sodium
TS - Total Solids
SS - Suspended Solids
AN - Ammoniz Nitrogen
ON Organic Nitrogen
COD - Chemical Oxygen Demand
Alk - Alkalinity
IS - Ionic Strength
+ - Linear Correlation
- - No-Linear Correlation

TABLE 17

LEACHATE CHEMICAL COMPOSITION DATA CORRELATION

From Day 1120 to Day 1300

*Entire system reached field capacity at 560 days

	VA	Lea	Fe	Zn	Ni	Cu	pH	Hard	PO_4	SO_4	Cl	Na	TS	SS	AN	ON	COD	Alk	IS	Day
VA	+																			
Lea	+	+																		
Fe	-	-	+																	
Zn	-	-	-	+																
Ni	-	-	+	-	+															
Cu	-	-	-	-	-	+														
pH	-	+	-	-	-	-	+													
Hard	-	-	+	-	-	-	-	+												
PO_4	-	-	-	-	-	-	-	-	+											
SO_4	-	-	-	-	-	-	-	-	+	+										
Cl	-	-	+	-	-	-	-	+	-	-	+									
Na	-	-	+	-	-	-	-	+	-	-	+	+								
TS	-	-	-	-	-	-	-	-	-	-	-	-	+							
SS	-	-	-	-	-	-	-	+	-	-	-	-	-	+						
AN	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+					
ON	-	-	+	-	-	-	-	+	-	-	+	+	-	+	-	+				
COD	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+			
Alk	-	-	+	-	-	-	-	+	-	-	+	+	-	+	-	+	-	+		
Is	-	-	+	-	-	-	-	+	-	-	+	+	-	+	-	+	+	+	+	
Day	-	-	+	-	+	-	-	+	-	-	+	+	-	-	-	-	+	+	+	+

VA - Volume Added
Lea - Leachate
Fe - Iron
Zn - Zinc
Ni - Nickel
Cu - Copper
Hard - Hardness
PO_4 - Phosphate
SO_4 - Sulfate
Cl - Chloride
Na - Sodium
TS - Total Solids
SS - Suspended Solids
AN - Ammonia Nitrogen
ON Organic Nitrogen
COD - Chemical Oxygen Demand
Alk - Alkalinity
IS - Ionic Strength
+ - Linear Correlation
- - No Linear Correlation

TABLE 18

LEACHATE CHEMICAL COMPOSITION DATA CORRELATION

From Day 1300 to Day 1485

*Entire system reached field capacity at 560 days

	VA	Lea	Fe	Zn	Ni	Cu	pH	Hard	PO_4	SO_4	Cl	Na	TS	SS	AN	ON	COD	Alk	IS	Day
VA	+																			
Lea	+	+																		
Fe	+	+	+																	
Zn	-	-	-	+																
Ni	-	-	-	-	+															
Cu	-	-	-	-	-	+														
pH	+	+	+	-	-	-	+													
Hard	+	+	+	-	-	-	-	+												
PO_4	-	-	-	-	-	-	-	-	+											
SO_4	-	-	-	-	-	-	-	-	-	+										
Cl	-	+	+	-	-	-	+	+	-	-	+									
Na	-	-	-	+	-	-	-	-	-	-	-	+								
TS	-	-	-	-	-	-	+	-	-	-	-	-	+							
SS	-	-	-	+	-	-	-	-	-	-	-	+	-	+						
AN	-	-	-	-	-	-	-	+	-	-	-	-	-	+	+					
ON	-	-	-	-	-	-	-	-	-	-	+	-	+	-	-	+				
COD	+	+	+	-	-	-	-	+	-	-	-	-	-	+	+	-	+			
Alk	+	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+		
Is	+	+	+	-	-	-	+	+	-	-	-	-	-	-	-	-	+	+	+	
Day	+	+	+	-	-	-	+	+	-	+	-	-	-	-	-	-	+	_	+	+

VA - Volume Added
Lea- Leachate
Fe - Iron
Zn - Zinc
Ni - Nickel
Cu - Copper
Hard-Hardness
PO_4- Phosphate
SO_4- Sulfate
Cl - Chloride
Na - Sodium
TS - Total Solids
SS - Suspended Solids
AN - Ammonia Nitrogen
ON - Organic Nitrogen
COD- Chemical Oxygen Demand
Alk- Alkalinity
IS - Ionic Strength
+ - Linear Correlation
- - No-linear Correlation

TABLE 19

LEACHATE CHEMICAL COMPOSITION DATA CORRELATION

From Day 1485 to Day 1670

*Entire system reached field capacity at 560 days

	VA	Lea	Fe	Zn	Ni	Cu	pH	Hard	PO_4	SO_4	Cl	Na	TS	SS	AN	ON	COD	Alk	Is	Day
VA	+																			
Lea	-	+																		
Fe	-	-	+																	
Zn	-	-	-	+																
Ni	-	-	-	-	+															
Cu	-	-	-	-	-	+														
pH	-	+	-	-	-	-	+													
Hard	-	-	-	-	-	-	-	+												
PO_4	-	-	-	-	-	-	-	-	+											
SO_4	-	-	-	-	-	-	-	-	-	+										
Cl	-	-	-	-	-	-	-	-	-	-	+									
Na	+	-	-	-	-	-	-	-	-	-	+	+								
TS	-	-	-	-	-	-	-	-	-	-	-	-	+							
SS	-	-	+	+	-	-	-	-	-	-	+	+	-	+						
AN	+	+	-	-	-	-	-	-	-	-	-	-	-	-	+					
ON	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+				
COD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+			
Alk	+	-	-	-	-	-	-	-	-	-	+	+	-	-	+	-	-	+		
Is	+	-	+	-	-	-	-	-	-	-	+	+	-	-	+	-	-	+	+	
Day	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	+

VA - Volume Added
Lea - Leachate
Fe - Iron
Zn - Zinc
Ni - Nickel
Cu - Copper
Hard - Hardness
PO_4 - Phosphate
SO_4 - Sulfate
Cl - Chloride
Na - Sodium
TS - Total Solids
SS - Suspended Solids
AN - Ammonia Nitrogen
ON - Organic Nitrogen
COD - Chemical Oxygen Demand
Alk - Alkalinity
IS - Ionic Strength
+ - Linear Correlation
- - No-linear Correlation

capacities. The soil cover, refuse and Ottawa sand-glass bead bed were placed in the lysimeter in a relatively dry state. As a result, a major portion of the water initially added was absorbed by each component until they reached their respective field capacities. This absorption was the cause of the difference between the two curves during the early portion of the test period. It is noteworthy that within one week after the initiation of the test, a small amount of leachate was obtained.

As the net quantity of water stored in the lysimeter increased (Figure 22), leachate production increased. A significant amount of leachate began to be produced by the lysimeter at approximately 430 days into the test. However, field capacity was not reached until approximately 550 days into the test. Thereafter, the relationship between input and output water indicated that once field capacity was attained within the soil-solid waste system, it was maintained throughout additional yearly cycles. In Figure 22 is shown the relationship between the computed water storage and the actual water stored in the soil-solid waste system during the yearly cycles.

The curve (Figure 22) shows that the actual water stored during a one year period cycles around the computed storage value. These results clearly establish the validity of the computation technique and graphically show the wetting and drying periods resulting from annual precipitation and evapotranspiration changes. The phase relationship between water added and leachate production is also evident from the curves. During periods of low leachate production any decreases in water input further reduced or eliminated leachate. The results show the cyclic nature of the annual water storage with a quasi-steady state condition existing once full field capacity was reached throughout the entire system.

Leachate production can be attributed to one or all of the following sources:

1. FROM THE REFUSE

   Most of the initial leachate is obtained from the refuse organic components and initial moisture content by the compaction and placement procedure.

2. FROM CHANNELING

   Some of the water added at the top of the lysimeter finds a direct route through the refuse to the collection trough, due to any refuse inhomogeneities.

3. FROM AN ADVANCED WETTING FRONT

   The wetting front in the refuse moves as a broad band rather than as a single-line interface. As a result, substantial increases in the leachate occur before the entire system is at field capacity.

4. FROM THE MAIN WETTING FRONT

   This is the leachate produced when the system reaches field capacity. At this stage, input water and leachate quantities become approximately equal.

From the curves presented in Figures 21 and 22, it may be concluded that sources 1 and 2 were responsible for the leachate collected during the early time period. Their influence on leachate collected during the latter time periods was negligible. Between 175 and 210 days, leachate production increased substantially. However, the amount of leachate produced was significantly less than the input water quantities. This behavior pattern can best be described by the one outlined as source 3. Finally, the the second year, leachate quantity increased to a level almost equal to input water quantities. This behavior indicated that the entire system was at about field capacity, and that a transition between source 3 and source 4 was occurring. Full field capacity, hence, source 4, existed during the remainder of the study.

Patterns of Leachate - Pollution Generation

Figures 23 through 52 are the graphical presentation of specific ions investigated in this study. Figures 53 to 69 are the graphical presentation of the means and standard deviations of these ions.

pH -

The curve in Figure 23 shows that pH variation, while highly erratic, was essentially bounded between 5.0 and 7.0. During the early portion of the test, variations were the most extreme, with the mean value being about 5.5 with a low of approximately 4.5 and a high of approximately 8.3. Periods when the leachate became basic correspond to low leachate flows. During the latter portion of the test period, pH values reached 6.5 with the overall trend being toward a "neutral solution" (pH-7).

It is believed that flow rate through the refuse is a major controlling factor in establishing leachate pH, and that with high flow rates, the pH will generally be acidic (See Tables 13 thru 19).

Generation of large quantities of acidic leachate compound pollution potential because low pH values reduce exchange capacities of renovating soil at the time when leachate quantities are high.

Iron -

The curve for iron concentration is presented in Figure 24. A comparison of Figure 24 with the leachate volume curve (Fig. 21) indicates that leachate volume had a significant influence on iron concentration.

During low leachate flow periods, iron concentrations were relatively low; when leachate quantities were high, there was a significant increase in iron concentrations. It is believed that this behavior pattern may be explained by the fact that during periods of low leachate volume, solution pH exceeded 5.5 and during periods of high leachate volume, solution pH was less than 5.5. Below a pH of 5.5., many iron salts, both ferric and ferrous, are soluble. Because of their ability to remain in solution, they are more easily removed from the refuse. Above a pH of 5.5, iron salts are less soluble, will precipitate and be filtered from the leachate either by the refuse or underlying materials.

Iron concentrations exceeded 1600 mg/l during the early periods of high leachate volume. Thereafter, a generally decreasing trend in concentration existed with local peaks. During the last two hundred days of the test period, iron concentrations were less than 200 mg/l and generally decreasing.

Figure 25 summarizes graphically the total iron per square foot of refuse horizontal surface area which was removed during the test. At the end of the test period, 48 grams per square foot (516.68 grams per sq. meter) had been removed with no sign of a maximum having been reached.

A plot of total grams per square foot versus the liters of leachate per square foot of refuse horizontal area is presented in Figure 26. System field capacity was reached at approximately 30 liters per square foot (323 liters per sq. meter). Thereafter, the semi-log plot tended to become linear. This plot shows that once field capacity is reached, the quantity of iron removed is primarily a function of the amount of leachate generated with local variations representing the infiltration variations due to changes in precipitation and evapotranspiration.

Zinc -

Leachate zinc concentrations are presented in Figure 27. Figure 28 shows the total zinc removed per square foot of refuse horizontal surface area. The most significant concentrations of zinc appeared in the leachate between 430 and 800 days of the test period. Thereafter, except for some small detectable concentrations, zinc removal was negligible. The period of high zinc removal corresponded to the first cycle of high leachate removal during the second year of the test. As shown in Figure 28, approximately 1.5 grams of zinc per square foot (16.15 grams per sq. meter) of refuse horizontal area were leached.

The curve in Figure 29 is a plot of grams of zinc per square foot of refuse leached vs. liter of leachate per square foot of refuse horizontal area. High zinc leaching occurred after field capacity was attained. The high period of zinc leaching was followed by a period in which little zinc was detected.

Phosphate -

The curve for leachate phosphate concentration is shown in Figure 30. While concentration levels reached 130 mg/l during the initial period of the test, thereafter concentration levels were markedly lower and irregular. The phosphate analysis was terminated because of lack of detectable concentrations over the last half of the test period, as well as a general lack of confidence in the test procedure.

Sulfate -

The curve in Figure 31 shows leachate sulfate concentrations. Sulfate tests were terminated due to detecting discrepancies in the testing procedure.

It is believed that the sulfate test results are inconclusive.

Chloride -

The chloride ion concentration curve is presented in Figure 32, and in Figure 33 leached chloride per square foot of refuse horizontal area is shown. Fig. 34 is leached chloride in grams per square foot of refuse horizontal area as a function of leachate in liters per square foot of refuse horizontal area.

While chloride was found in the leachate during the entire test period, the highest concentrations occurred between days number 200 and 350. During the high concentration period, the chloride reached as high as 2400 mg/l. Over most of the period, chloride concentrations ranged between 300 and 600 mg/l. However, during the last 200 days of the study, chloride concentrations were less than 200 mg/l.

The curve showing chloride removed per square foot of refuse horizontal area (Figure 33) indicates that most of the available chloride had been removed during the test period.

The semi-log plot in Figure 34 shows that once field capacity has been reached, a linear relationship exists between the quantity of chloride removed and the volume of leachate.

Sodium

Figure 35 is the sodium ion concentration curve. Figure 36 is the total grams of sodium leached per square foot of refuse horizontal area.

The curve in Figure 35 shows that, in general, sodium concentrations ranged between 500 and 1000 mg/l after an initial high concentration period in which peaks of between 2000 mg/l and 3400 mg/l were reached. During the last two hundred days of the test period, concentrations levels were negligible.

Almost 40 grams of sodium per square foot (430.6 grams per sq. meter) of refuse horizontal area were removed during the test period with a complete removal being approached at the termination of the test.

The semi-log curve shown in Figure 37 indicates that a well defined relationship exists between the quantity of sodium leached per square foot of refuse horizontal area and the liters of leachate per square foot, once field capacity was attained.

Nitrogen -

The nitrogen data is presented for both organic and free ammonia forms in Figures 38 through 42. Organic nitrogen concentrations ranged between 50 mg/l and 200 mg/l during the first half of the study, did not exceed 100 mg/l during the second half of the study, and reached negligible levels at the end of the study. From Figure 39, it can be seen that most of the organic nitrogen had been removed by the end of the test.

Although not as sharply defined as in some of the other cases, a semi-log relationship between organic nitrogen leached per square foot of refuse horizontal area and liters of leachate per square foot of refuse horizontal area can be seen in Figure 40.

The graphical presentations for the ammonia nitrogen fail to show any unique relationships for either the time or leachate per square foot of refuse horizontal area independent variables.

Hardness (as $CaCO_3$) -

Figure 43 is the hardness concentration curve. As can be seen, a peak occurred at 5500 mg/l at 420 days into the test. However, concentrations usually did not exceed the 1500 mg/l to 2500 mg/l levels with most being near the lower value. During the latter part of the test period, concentrations were in the 200 to 400 mg/l range.

The quantity of hardness per square foot of refuse horizontal area versus time curve (Figure 44) indicates that hardness removal occurred in slugs with the high removal periods coinciding with periods of peak leachate flows resulting in the removal of the most quantities of hardness.

The semi-log plot in Figure 45 shows a well defined linear relationship between quantity of hardness and quantity of leachate once field capacity has been attained.

Chemical Oxygen Demand -

Figure 46 shows that chemical oxygen demand concentrations were in excess of 50,000 mg/l within one month of the initiation of the test. It is believed that this initial peak was caused by the release of some of the organic components due to the refuse compaction and placement process. Over the first 1200 days of the test the chemical oxygen demand was cyclic with peaks in the 20,000 mg/l to 25,000 mg/l range. High concentrations occurred during low leachate flow periods. Between 1000 and 1200 days the chemical oxygen demand peaked at between 10,000 mg/l and 15,000 mg/l. Thereafter and for the remainder of the test period the chemical oxygen demand decreased to the 2000 mg/l to 3000 mg/l levels with substantially lower values frequently being attained.

Figure 47 shows that toward the end the the test period the amount of chemical oxygen demand became negligible.

The semi-log curve in Figure 48 shows a reasonably good linear relationship between the quantity of chemical oxygen demand and the leachate volume.

Total and Suspended Solids -

The curve for total solids concentration is shown in Figure 49 and the curve for suspended solids concentrations is shown in Figure 50.

Total solids concentrations peaked at approximately 40,000 mg/l at 800 days into the test. Usual total solids ranged between 20,000 mg/l and 25,000 mg/l in the first half of the test period and did not exceed 10,000 mg/l during the second half of the test period. At the end of the test, total solids concentrations were approximately 1000 mg/l.

Suspended solids concentrations (Figure 50) were very irregular. Most suspended solids concentrations fell between 400 mg/l and 1000 mg/l with a peak of 1800 mg/l at 700 days into the test. During the final portion of the test period concentrations of suspended solids were about 100 mg/l.

Nickel -

The nickel ion concentration curve is presented in Figure 51. No nickel was detected prior to 150 days of elapsed test time. After that time, nickel was present in concentrations of approximately 0.2 mg/l to 0.3 mg/l with peaks at 0.8 mg/l and 1.0 mg/l. Due to the low concentrations the test was terminated after 1200 days of test.

Copper -

The copper ion concentration curve is presented in Figure 52. A peak of 4.7 mg/l occurred at 150 days and a peak of 9.8 mg/l occurred at 590 days. Generally, concentration levels were less than 1.0 mg/l. Due to the low concentrations the test was terminated after 1200 days of test.

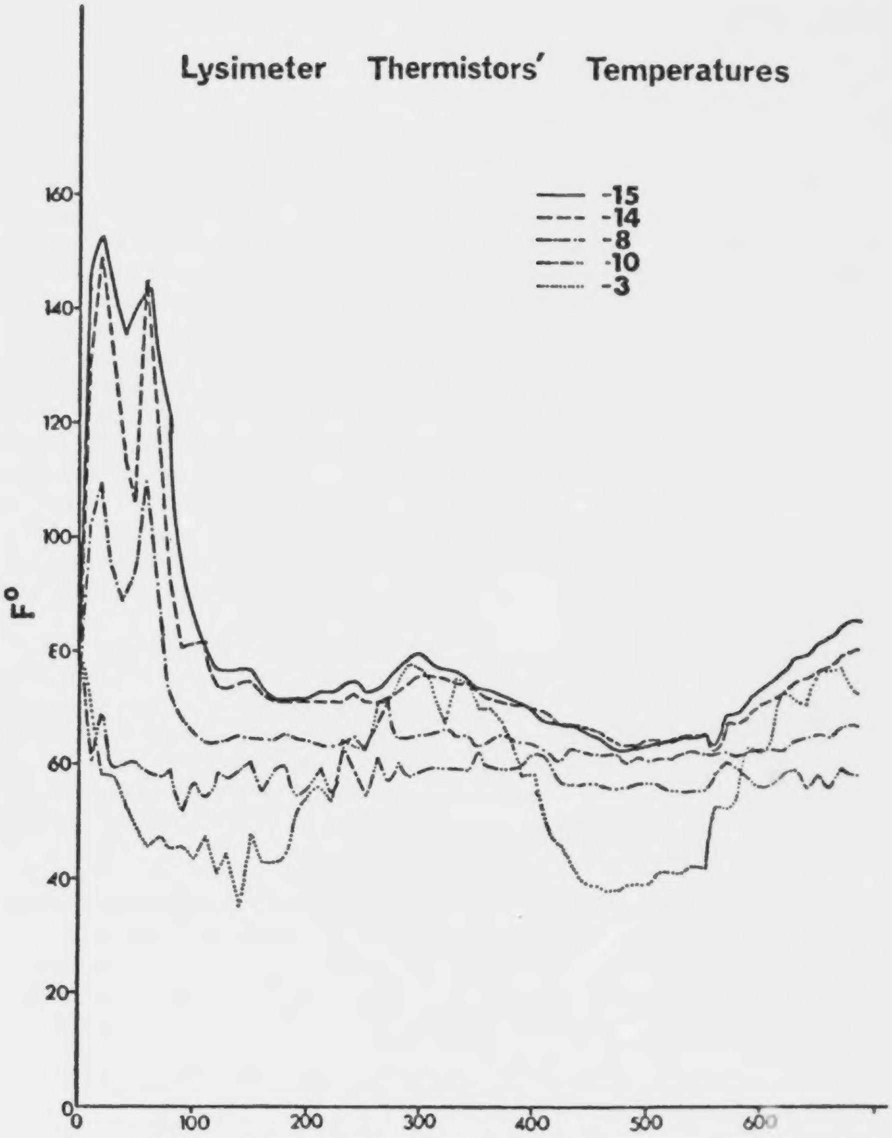
Lysimeter Temperatures -

Curves for temperatures at various locations within the lysimeter are presented in Figure 70. The dotted curve (number 3) represents the average monthly air temperatures, as listed in Table 1. The general pattern of initial temperature behavior can be described as a rapid increase in the temperature at the refuse center followed by a slower rate of increase at adjacent levels. The center temperature peaked at 154°F, whereas temperatures at adjacent levels did not exceed 143°F, and generally were not in excess of 110°F to 115°F. The temperature distribution pattern indicates that temperatures in the layers of refuse adjacent to the center layer initially increased due to a spreading effect as heat flowed to both the top and bottom temperature controlled boundaries. The initial temperature distribution appeared to be controlled by conditions at the refuse center. Once adjacent levels reached their temperature peaks (after approximately 60 days), all temperatures showed a continuous gradual decline until virtually steady state temperatures prevailed.

The rapid temperature increase at the refuse center to a peak of 154°F is of particular interest in that the rise occurred within 20 days of test initiation. Temperatures then slowly decreased until a 60 day time period had elapsed and, thereafter, rapidly decreased to a temperatue of approximately 80°F. The initial increase in temperatures at the refuse center was independent of temperature change at other refuse levels.

The temperature behavior pattern described indicates that the system was initially controlled by general aerobic conditions in the refuse, and that after a 60 day period, anaerobic conditions dominated. Also of interest is that once the internal temperatures became virtually steady state, and the refuse anaerobic, changes in top boundary temperature (bottom boundary temperature was held constant at 57.2°F) had little effect on them.

While temperatures were recorded throughout the entire test period, the curve in Figure 70 covers only through the time when the system became completely anaerobic. Once anaerobic, temperature patterns continued as shown in the latter portion of Figure 70.



Lysimeter Thermistors' Temperatures
-15
-14
-8
-10
-3
160
140
120
100
80
60
40
20
0
F°
0
100
200
300
400
500
600
Time in Days from October 1, 1967

FIGURE 70

Lysimeter Gases -

Gases were obtained at the four port locations and analyzed on a routine basis for carbon monoxide, hydrogen sulfide, nitrogen, carbon dioxide and methane. No carbon monoxide or hydrogen sulfide were detected. The curves in Figures 71 through 78, for methane and carbon dioxide are presented as a percentage of total gas present at the time of sampling. The average oxygen contents for various time periods are tabulated on the methane curves. Nitrogen, which made up the remaining percentage of the total is not included with the curves.

The results presented in Figures 71 and 72 for the top port indicate that at that level the gas quality was primarily that of air. There was some buildup of methane and carbon dioxide between 500 and 1000 days. However, methane levels were generally less than five percent.

The gas concentrations for the other ports showed increasing percentages of methane and carbon dioxide with depth and a corresponding decrease of oxygen. Significant quantities of methane began to appear 100 days after test initiation. Oxygen, although of low quantity, was detectable at all levels over the entire test period. Carbon dioxide was present over the entire test period in amounts which increased slightly with depth.

Methane levels initially increased with depth and time. At the second port they reached as high as thirty percent at approximately 600 days into the test. The most usual methane concentrations ranged between ten and twenty percent. At port number three, methane levels reached as high as forty percent with concentration frequently between twenty and thirty percent.

Maximum methane concentrations at the fourth port did not exceed thirty-five percent with concentrations between twenty and thirty percent.

Methane generation was at a maximum at all levels between approximately 400 and 800 days into the test. A significant decrease of methane occurred between approximately 1100 and 1300 days into the test. While the lull period was followed by a regeneration of methane at all levels, concentrations were generally significantly less than previously detected. Further, at the end of the test, methane concentrations were substantially lower than the recorded peak and decreasing.

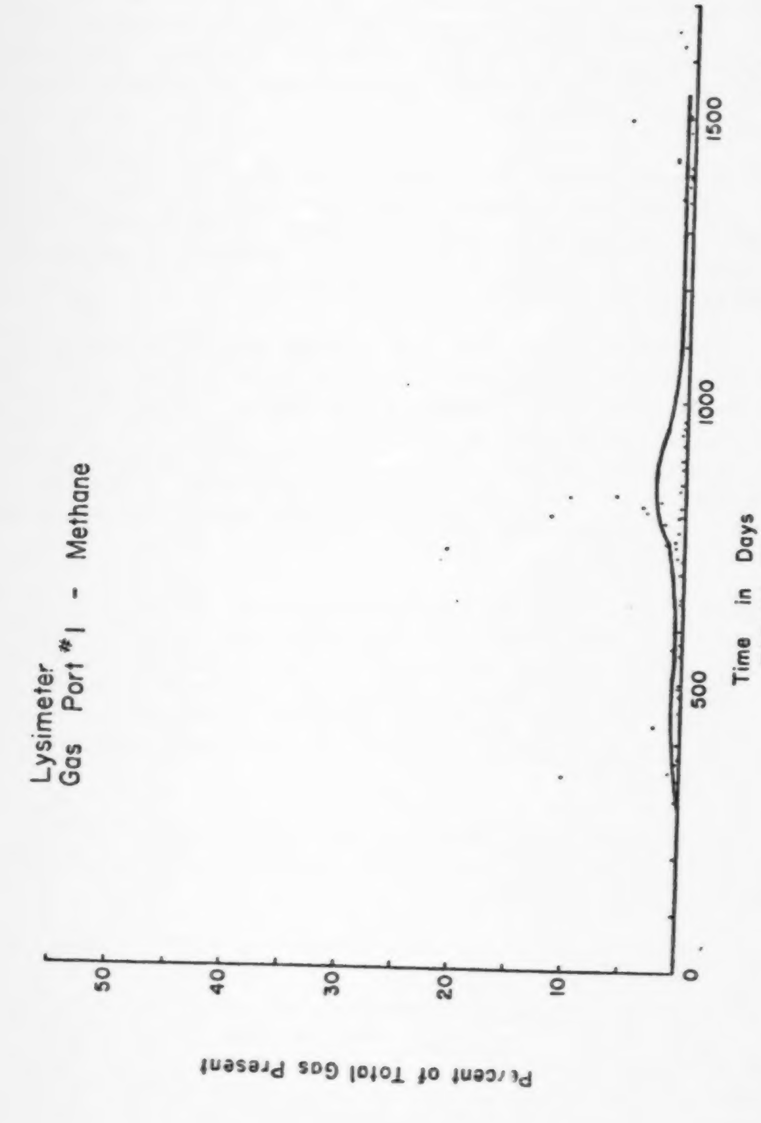

Lysimeter
Gas Port #1 - Methane
Percent of Total Gas Present
0
10
20
30
40
50
0
500
1000
1500
Time in Days

FIGURE 71

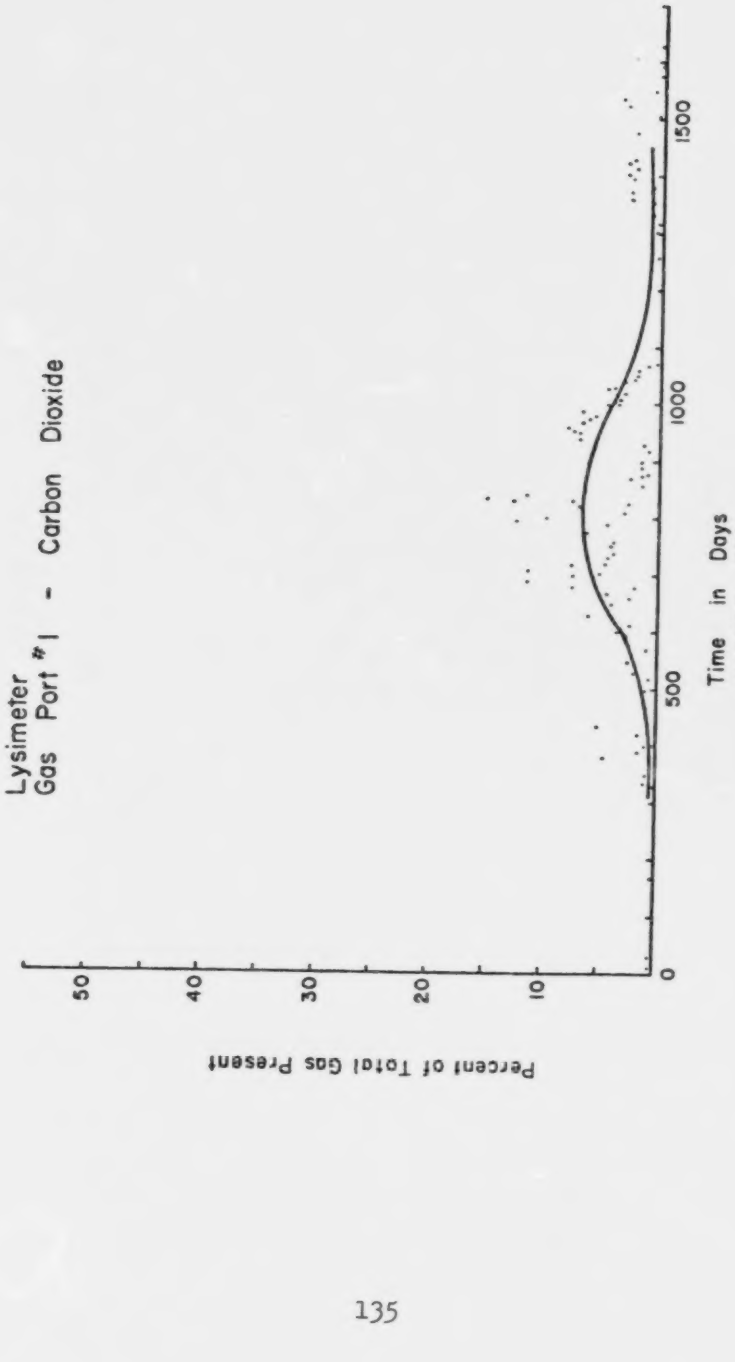
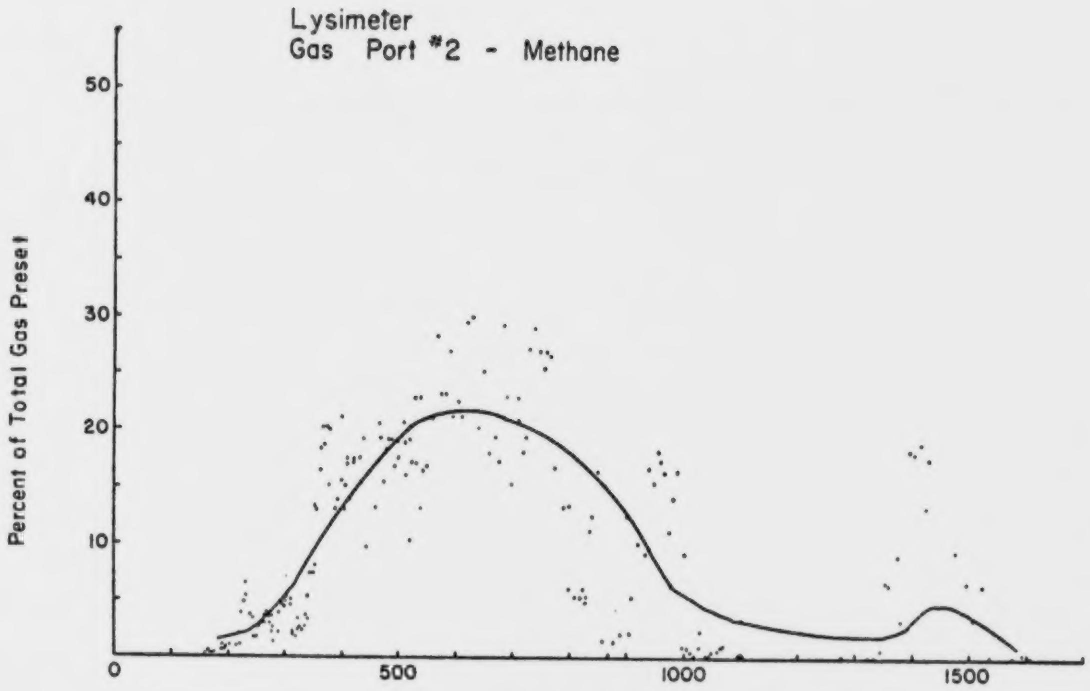

Lysimeter
Gas Port #1 - Carbon Dioxide
Percent of Total Gas Present
50
40
30
20
10
0
500
1000
1500
Time in Days

FIGURE 72



Lysimeter
Gas Port #2 - Methane

FIGURE 73

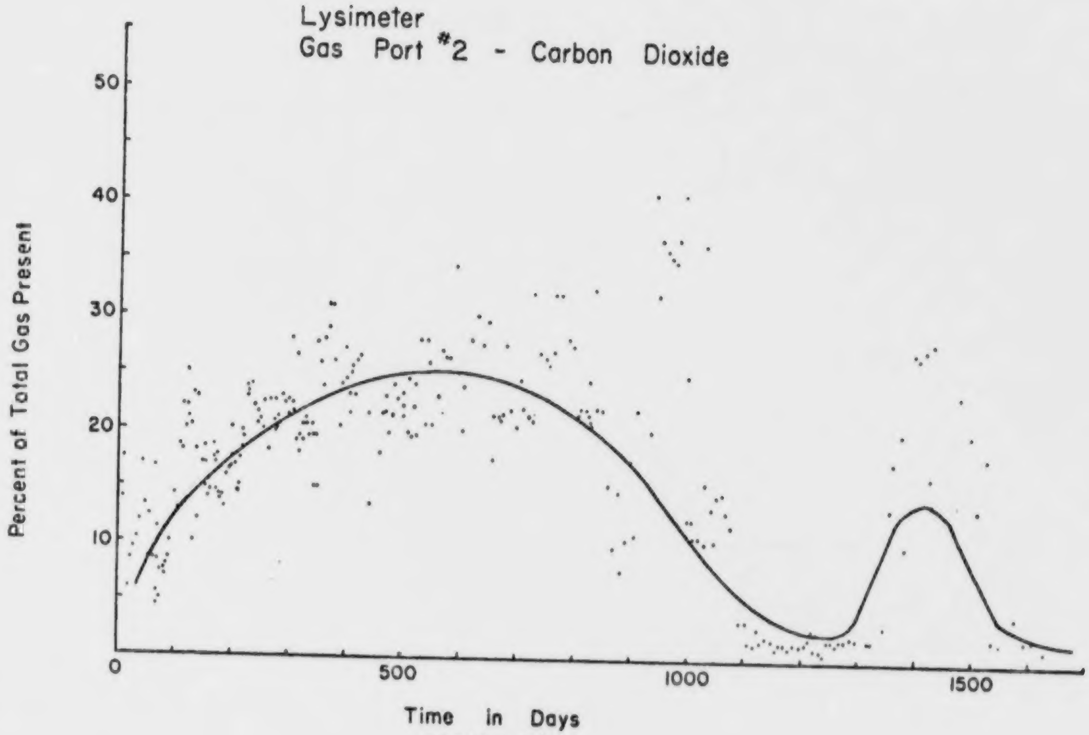

Lysimeter
Gas Port #2 - Carbon Dioxide
Percent of Total Gas Present
50
40
30
20
10
0
500
1000
1500
Time in Days

FIGURE 74

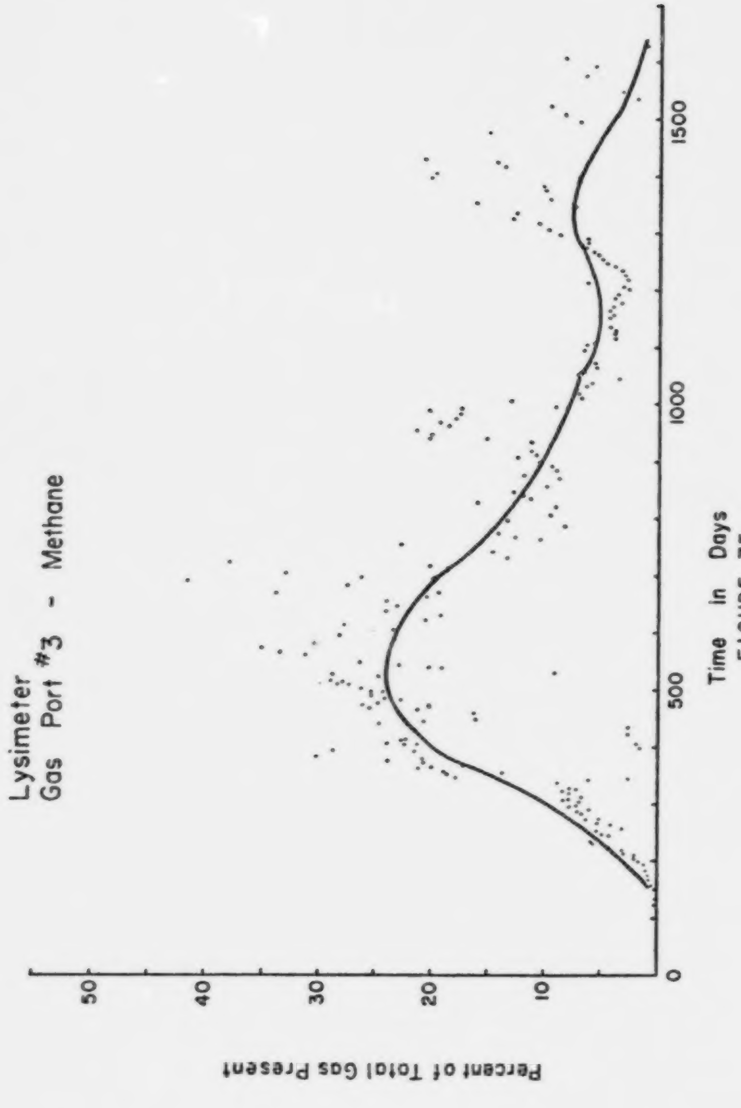

Lysimeter
Gas Port #3 - Methane
Percent of Total Gas Present
0
10
20
30
40
50
500
1000
1500
Time in Days

FIGURE 75

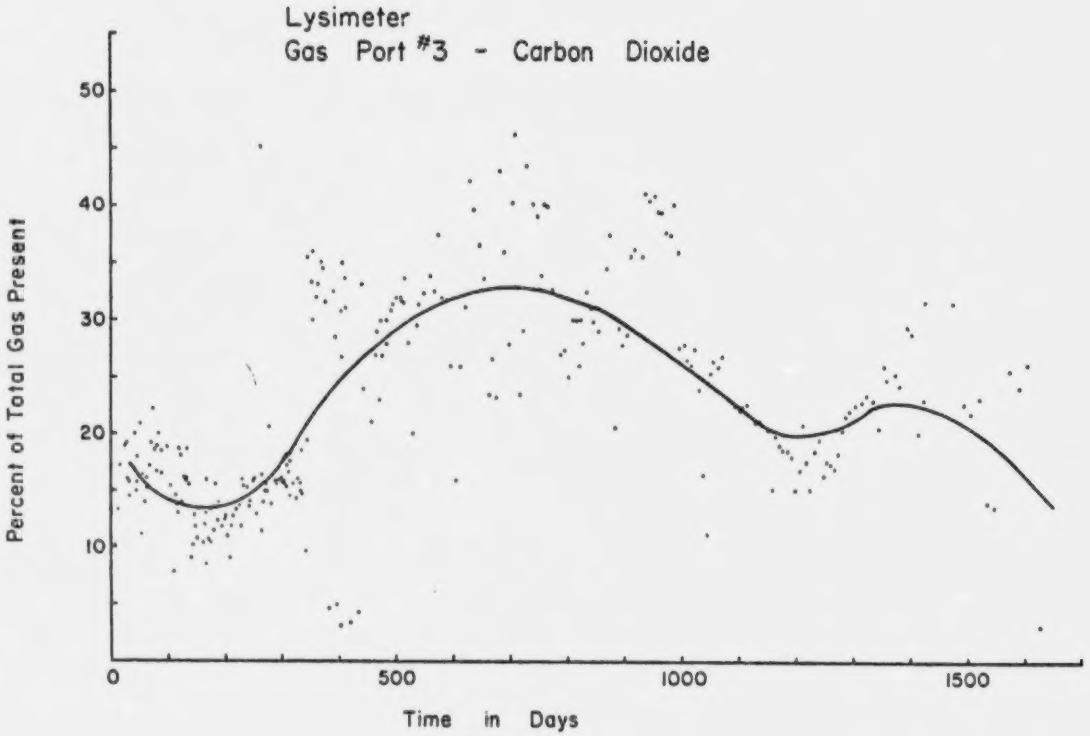

Lysimeter
Gas Port #3 - Carbon Dioxide
Percent of Total Gas Present
50
40
30
20
10
0
500
1000
1500
Time in Days

FIGURE 76

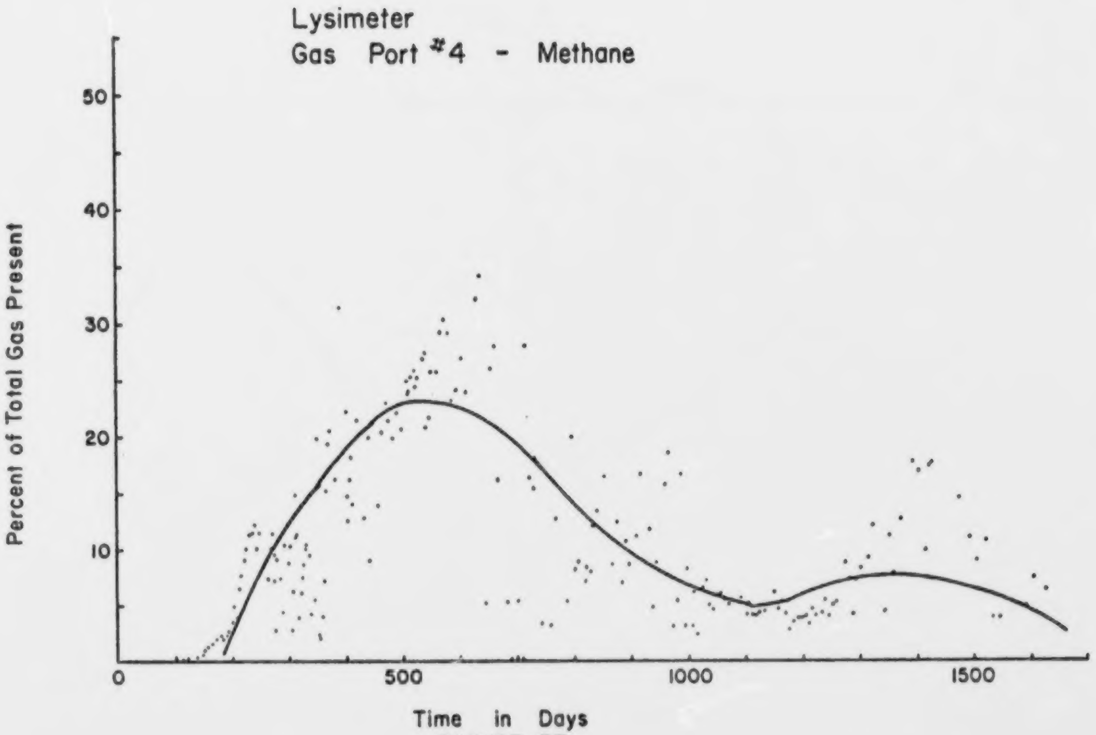
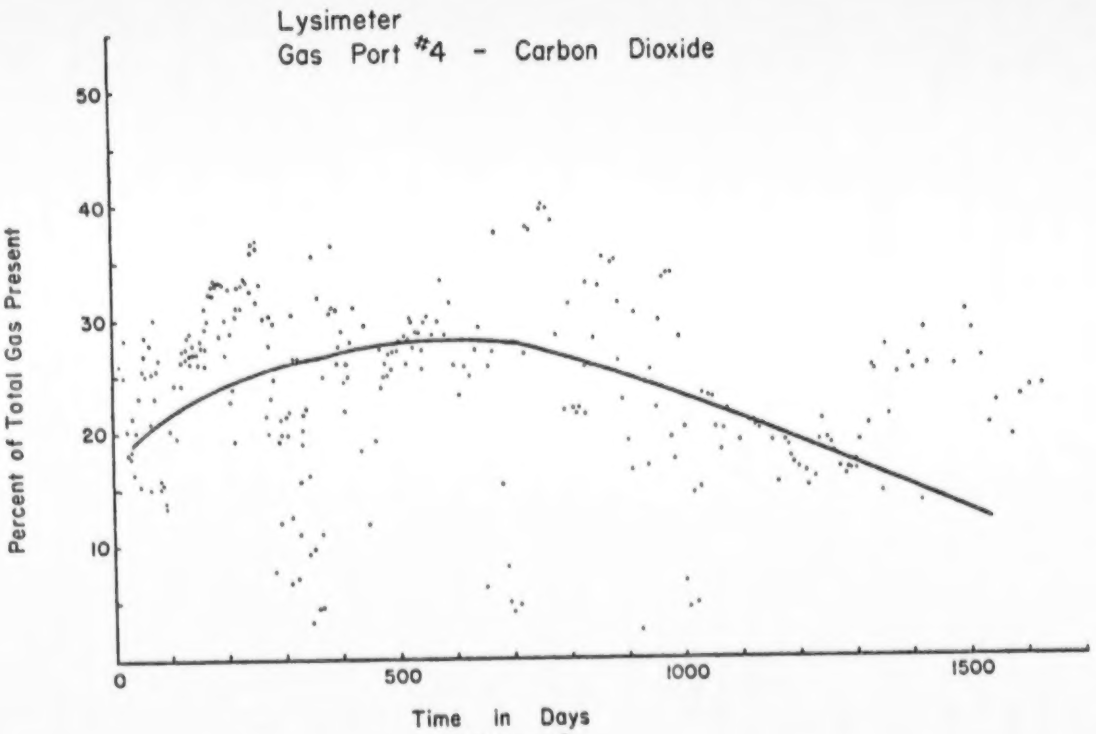

Lysimeter
Gas Port #4 - Methane
Percent of Total Gas Present
50
40
30
20
10
0
500
1000
1500
Time in Days

FIGURE 77



Lysimeter
Gas Port #4 - Carbon Dioxide

FIGURE 78

From the temperature data (Fig. 70), it is seen that after the initial transient condition, initial temperatures decreased and were almost non-varying. The temperature levels and the behavior pattern indicates the existence of an anaerobic state within the refuse after the initial high temperature period. However, the gas data, particularly the continued existence of oxygen, indicates that aerobic pockets also existed in the refuse even at the deeper regions. From this data, it is concluded that pockets of aerobic and anaerobic activity can exist concurrently within the refuse. That such a behavior pattern was possible is not surprising considering the heterogeneous nature of the refuse and the young age of the landfill.

Lysimeter Solid Waste Final Chemical Composition

Table 20 summarizes the chemical composition of the solid waste used in the lysimeter. The data is for the solid wastes' initial composition and its composition after approximately four and one-half years of controlled leaching. The post-test compositions are for layers of refuse approximately twelve (12) inches (.305 m.) thick. The data is presented for each twelve (12) inch (.305 m.) layer starting from underneath the soil cover.

There are three significant conclusions which can be reached from the data presented in Table 20.

First, there is a substantial reduction in the inorginic water soluble components at all levels. While it is difficult to generalize on the percent reductions, decreases of the order of 75 to 90 percent are common.

Second, the upper layers of refuse tend to exhibit a higher degree of removal of inorganic leachable material than the lower layer. This suggests that the leaching process is progressive through the refuse deposit. It is not possible to determine if the higher concentrations in the lower layers are a result of filtration of the migrating leachate or due to a lack of removal of specific ions.

Third, the organic component measured by percent ether extractable shows not only an increase with depth, but also shows quantities greater than originally extracted. This suggests that during the test period a biological conversion of cellulose to a lower order organic substance occurs. This process would keep the Chemical Oxygen Demand of the leachate higher than expected from the initial chemical analysis. This observation is supported by the fact that the Chemical Oxygen Demand in the lysimeter leachate gen-

TABLE 20

Lysimeter Solid Waste Chemical Analysis
(mg/g of refuse - except as noted)

	Pre-Test Composition[1]	Post-Test Composition/layer[2]					
		1st	2nd	3rd	4th	5th	6th
Percent Ether Extractable	1.62	0.423	0.521	2.52	2.20	2.359	2.634
Percent Water Extractable	6.78	1.402	2.506	1.95	2.86	6.128	5.33
Solid Chemical Oxygen Demand	1283	733	768	960	981	1045	1086
Solid Nitrogen	2.97	1.95	2.29	0.0	0.0	0.0	1.42
Iron	0.602	0.091	0.112	0.101	0.587	0.050	0.036
Zinc	0.595	0.011	0.017	0.005	0.002	0.021	0.023
Nickel	0.034	0.021	0.011	0.022	0.029	0.056	0.029
Copper	0.025	0.007	0.005	0.011	0.007	0.009	0.007
Calcium	0.856	0.338	0.376	0.540	0.668	0.881	0.746
Phosphate	0.293	0.006	0.001	0.008	0.012	0.002	0.001
Chloride	2.003	0.200	0 211	0.259	0.126	0.299	0.578
Sodium	1.950	0.095	0.043	0.099	0.467	0.635	0.683
Ammonia Nitrogen	0.02	0.019	0.0	0.001	0.0	0.0	0.0
Organic Nitrogen	0.35	0.006	0.044	0.075	0.111	0.111	0.157
Chemical Oxygen Demand	25.25	1.25	0.943	3.063	8.46	11.83	10.47

1. Average of all refuse placed in lysimeter.

2. Average of four samples in each layer. Each layer approximately twelve inches (.305 m.) thick. First layer taken from top of refuse. Sixth layer taken from bottom.

erated from the final solid waste composition is substantially higher than are the inorganic components.

MINI-LYSIMETER

The mini-lysimeter studies were conducted over approximately a two year period. The results are summarized graphically in this section and tabulated in the data volume.

Mini-Lysimeter Temperatures

Temperature measurements were begun immediately after the refuse was placed in the mini-lysimeters. Temperatures were recorded monthly after the first two weeks during which time temperatures were recorded daily. Complete temperature data are tabulated in the data volume. The maximum temperature reached in each mini-lysimeter is given in Table 21. Temperature curves for mini-lysimeters K and M are presented in Figure 79.

Initially all temperatures were 5^{o}-15^{o} Fahrenheit above ambient. It is believed that the initial rise is a result of aerobic decomposition of the organic portion of the refuse. Because of the heat loss through the sides of the mini-lysimeter and the large quantities of water (19-38 liters) added to each unit to achieve field capacity, temperatures decreased substantially within the first three days. The temperature curve for lysimeter K in Figure 79 is considered typical of all the mini-lysimeter units except M.

Mini-lysimeter M was the only unit whose temperature pattern deviated significantly from the pattern represented by the curve for unit K. Mini-lysimeter M was fed water following the seasonal water regimen used in the large lysimeter. Further, its water feed cycle was started at a relatively dry period. As a result, no appreciable amounts of water were added to M after the initial additive of 19 liters. The 19 liters of water brought the initial moisture content of the refuse to one-half of field capacity.

Initial temperatures in mini-lysimeter M were substantially higher than ambient. Decreases to slightly above ambient occurred only after large quantities of water were added to the unit.

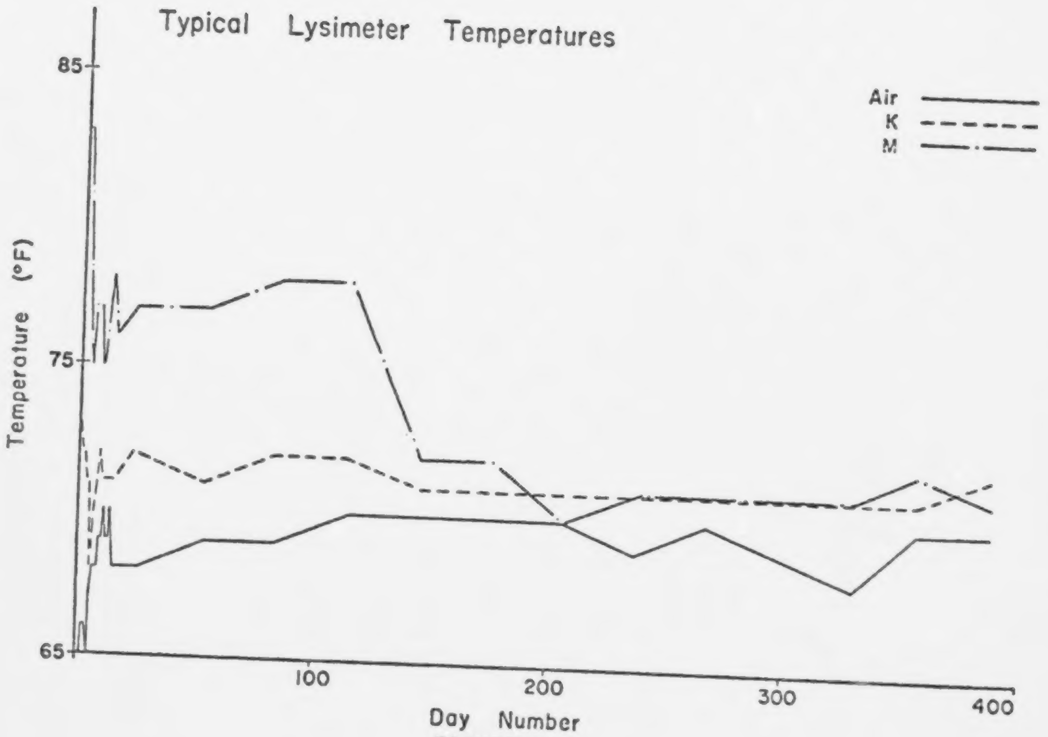
The results of the study indicate that temperature is an unreliable indicator of leachate concentration within the refuse. However, the results do clearly indicate a relationship between water infiltration and refuse temperature levels.

TABLE 21

Milled Refuse
Maximum Temperatures

D_{50}	Dry Density lbs/yd^3	Mini-Lysimeter	Maximum Temperature [a]
3.20	522.74	K	73.0
3.20	503.60	M	83.0
3.20	736.67	N	72.0
3.20	649.97	O	81.5
92.00	520.30	P	82.5
0.89	532.26	R	73.0
13.50	519.60	S	71.0

[a] Fahrenheit



Typical Lysimeter Temperatures

FIGURE 79

Mini-Lysimeter Gases

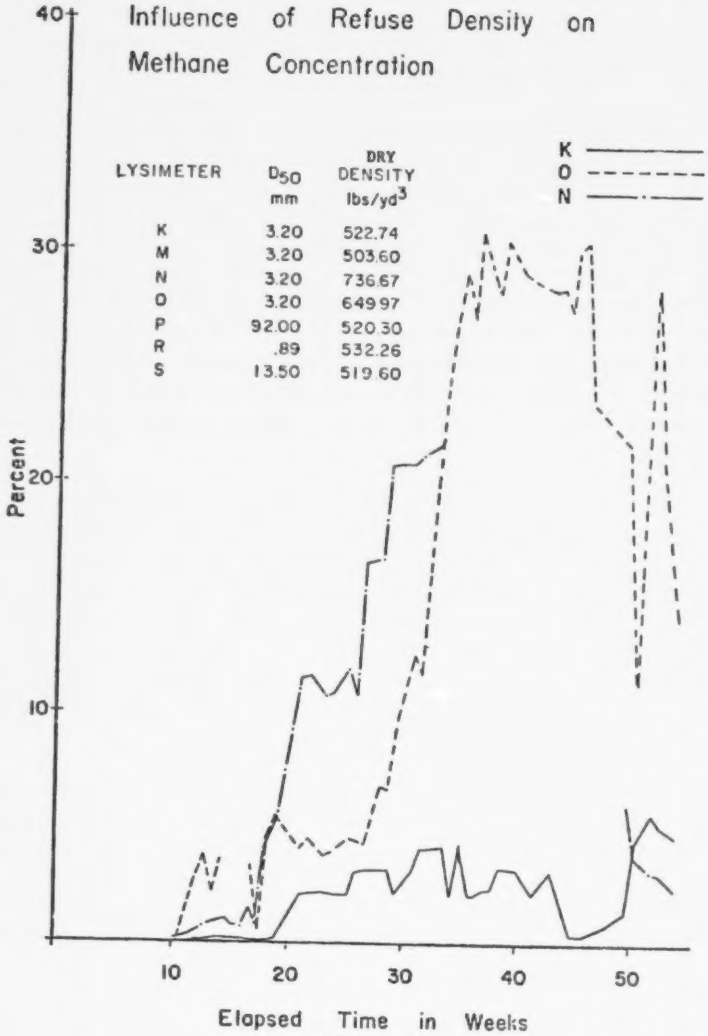
Gas samples were analyzed on a routine basis for carbon monoxide, hydrogen sulfide, nitrogen, oxygen, carbon dioxide and methane. No carbon monoxide or hydrogen sulfide were detected. Complete gas data are presented in the data volume. In Figure 80 are presented curves showing the relationship between milled refuse density and methane concentration. The relationship between milled refuse size and methane concentration is shown in Figure 81. Table 22 summarizes the maximum concentrations of carbon dioxide and methane reached in each of the mini-lysimeters.

The first gas samples were obtained one week after placement of the milled refuse. These initial samples indicated that carbon dioxide was high and that oxygen was greatly decreased. However, it took approximately four months before any measurable methane was obtained. From the curves in Figures 80 and 81, several observations can be made about the relationship between methane concentrations with time and milled refuse density and size. Higher refuse densities result in higher percentages of methane. The finer refuse sizes produce higher methane concentrations and the constant water feeding program also increases the methane concentrations.

The methane concentrations for milled refuse N, the densest, were significantly greater than the other sizes during the early test period. However, the gas probe for "N" clogged and no further samples could be taken. The maximum concentrations that would have been reached could only be speculated. However, the methane to density relationship is clear. It is noteworthy that the concentrations of oxygen and carbon dioxide in mini-lysimeters K, N and O were similar and somewhat constant.

The effect of milled refuse size on methane concentration is clearly shown in Figure 81. There is a gradual increase in methane concentrations with decreasing size down to D_{50} = 3.5 mm. For D_{50} = 0.89 mm., the methane concentration increases approximately 800 percent. The carbon dioxide and oxygen percentages reamined fairly constant.

Some variations from the norm are noteworthy. In mini-lysimeter R, carbon dioxide percentages increased during the test to a maximum of 44.5 percent which is significantly greater than levels reached in the other units. In mini-lysimeter P, carbon dioxide percentages were higher initially than in the other units and then showed a steadily decreasing trend. In addition to the decreasing trend in



LYSIMETER	D_{50} mm	DRY DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 80

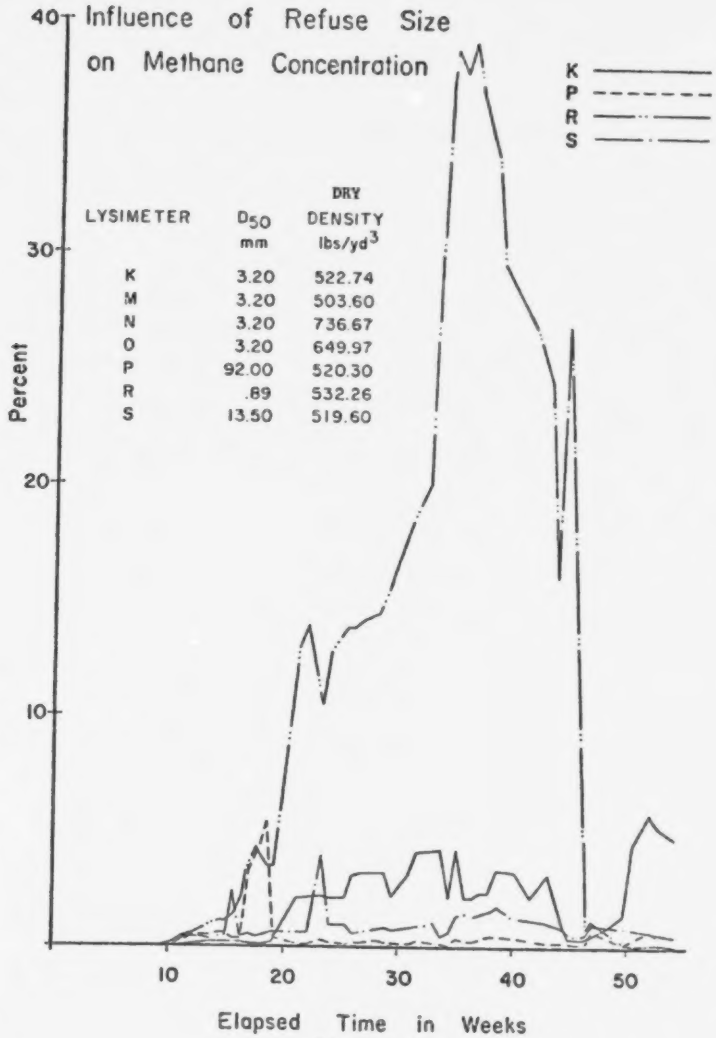

Influence of Refuse Size
on Methane Concentration
K
P
R
S
LYSIMETER
D50 mm
DRY DENSITY lbs/yd3
K 3.20 522.74
M 3.20 503.60
N 3.20 736.67
O 3.20 649.97
P 92.00 520.30
R .89 532.26
S 13.50 519.60
Percent
40
30
20
10
10
20
30
40
50
Elapsed Time in Weeks

FIGURE 81

TABLE 22

Maximum Gas Percentages

Lysimeter	D_{50}	Dry Density lbs/yd^3	Percent Carbon Dioxide	Percent Methane
K	3.20	522.74	30.5	5.7
M	3.20	503.60	28.5	0.8
N	3.20	736.67	32.3	22.0*
O	3.20	649.97	29.5	30.8
P	92.00	520.30	37.2	5.4
R	0.89	532.26	44.5	38.8
S	13.50	519.60	29.1	4.0

*Gas port clogged - sampling discontinued 2/16/71 carbon dioxide in mini-lysimeter P, oxygen levels increased after twenty-five weeks.

Milled Refuse Moisture Parameter Studies

Milled Refuse Field Capacity -

Field capacities were obtained for various size milled refuse compacted to several different densities. Initially the field capacity tests were performed on the milled refuse as compacted at its original moisture content. However, the results obtained did not prove satisfactory.

The procedure used to develop the results presented herein consisted of compacting the milled refuse into three (3) inch (76.2 mm.) diameter cyclinders and then immersing them in water and allowing the water to flow up into the container. The samples remained immersed for 48 hours by which time the refuse-free surface was covered with water. The samples were then tested following the procedure described in Appendix I.

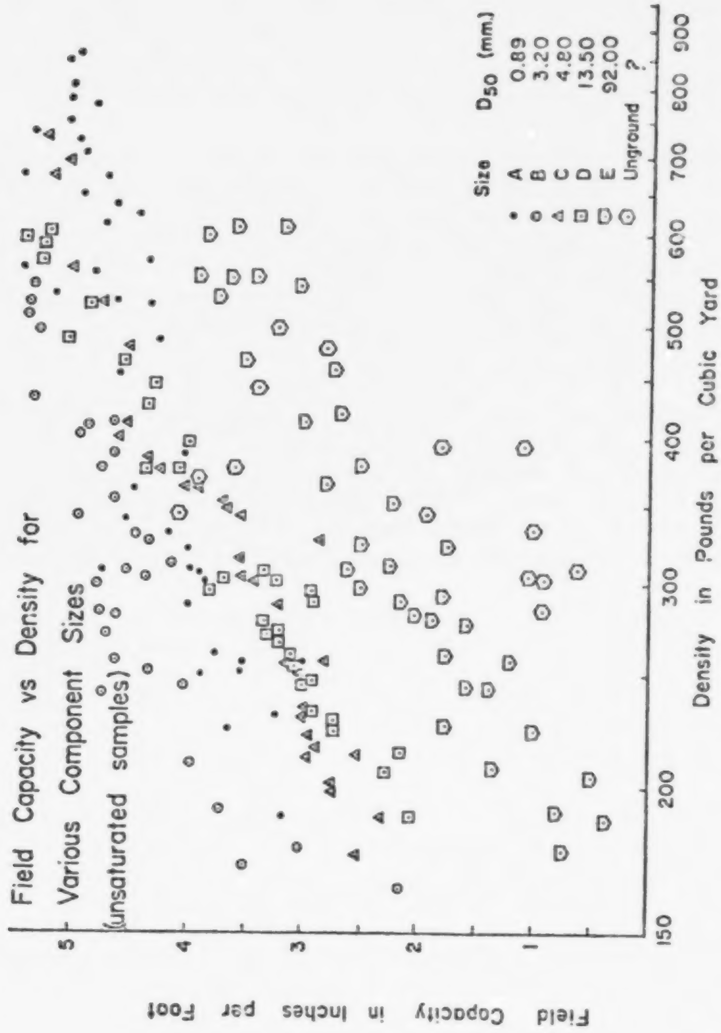
Upon completion of the field capacity tests, analysis of samples from the cylinders indicated that zones existed within the milled refuse which were still dry. On the finest mill size these "dry" pockets had moisture contents less than 10% higher than the original moisture content. The results of this study are presented in Figure 82.

As an alternate to the wetting scheme described above, refuse samples were first saturated, allowed to drain, and then subjected to the field capacity test described in Appendix II. This procedure insured complete wetting of the sample and better reproducibility of test results. The results of this study are presented in Figure 83.

Both Figures 82 and 83 present a plot of field capacity against the natural logarithm of the density. In Table 23 is tabulated the results of a least squares fit of the data for the various milled refuse sizes.

An attempt was made to establish saturated permeability for the various sizes of milled refuse. These results are presented in Figure 84. Overall, the results proved inconclusive and significant relationships between saturated permeability, density and milled refuse size could not be established.

The large variations in the experimental results can be attributed to the sample size,cylinder sidewall effect and



Field Capacity vs Density for Various Component Sizes (unsaturated samples)

FIGURE 82

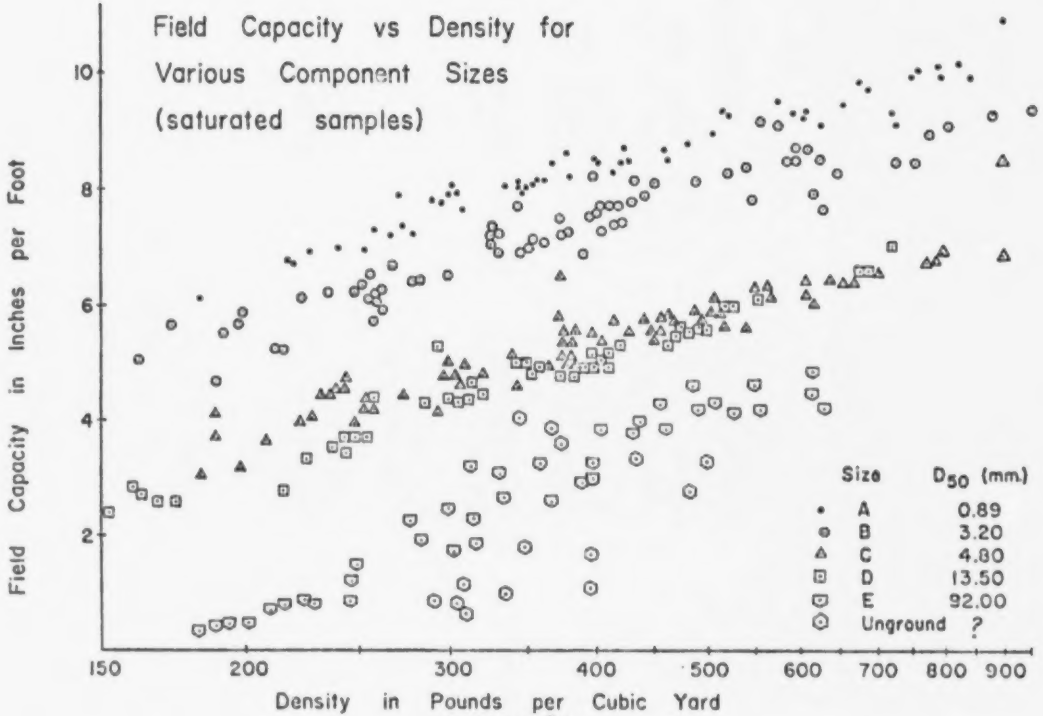

Field Capacity vs Density for
Various Component Sizes
(saturated samples)
Field Capacity in Inches per Foot
10
8
6
4
2
150
200
300
400
500
600
700
800
900
Density in Pounds per Cubic Yard
Size
D_{50} (mm)
● A 0.89
○ B 3.20
△ C 4.80
▣ D 13.50
▽ E 92.00
⬡ Unground ?

FIGURE 83

TABLE 23

Relationship of Density vs. Field Capacity

Size	D_{50} mm.	Saturated or Unsaturated	Equation
A	0.89	Saturated	$Y = 2.4527 \ln X - 6.3673$
A		Unsaturated	$Y = 1.23156 \ln X - 3.072$
B	3.20	Saturated	$Y = 2.5970 \ln X - 8.0894$
B		Unsaturated	$Y = 1.65921 \ln X - 5.1234$
C	4.80	Saturated	$Y = 2.2652 \ln X - 8.3397$
C		Unsaturated	$Y = 2.16418 \ln X - 8.9120$
D	13.50	Saturated	$Y = 3.02986 \ln X - 13.0421$
D		Unsaturated	$Y = 2.78459 \ln X - 12.4176$
E	92.00	Saturated	$Y = 3.75126 \ln X - 19.2754$
E		Unsaturated	$Y = 3.0578 \ln X - 18.7358$

Where Y = Field Capacity in Inches
per foot of refuse

X = Density of refuse

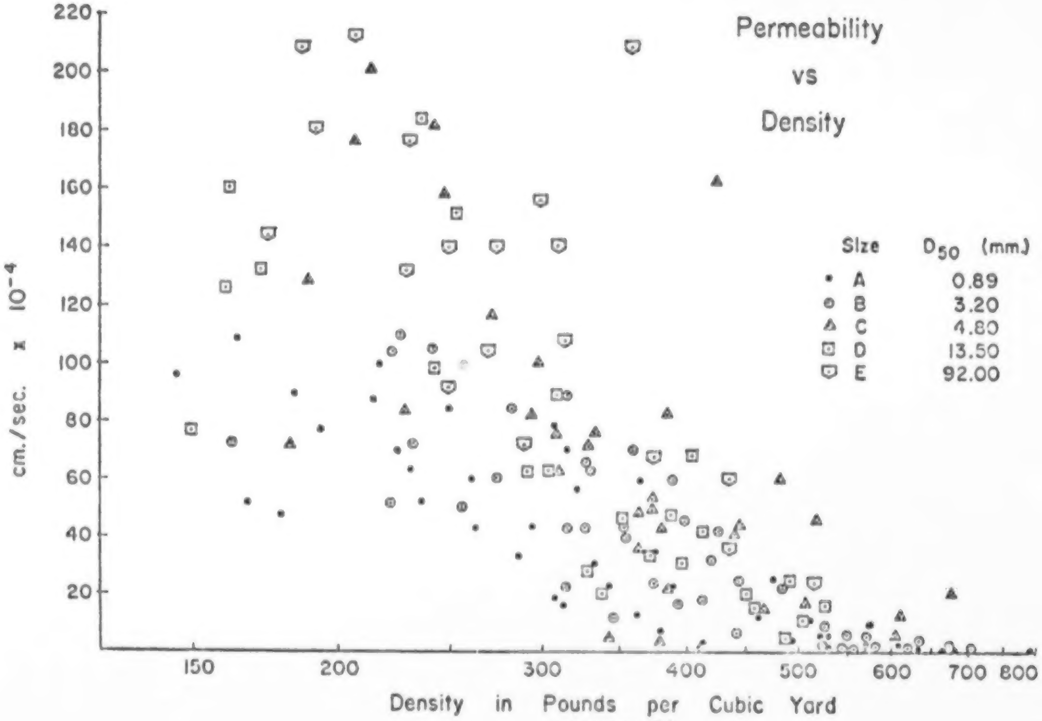

Permeability
vs
Density
Size D50 (mm.)
● A 0.89
⊙ B 3.20
▲ C 4.80
⊡ D 13.50
⊡ E 92.00
cm./sec. x 10-4
220
200
180
160
140
120
100
80
60
40
20
150
200
300
400
500
600
700
800
Density in Pounds per Cubic Yard

FIGURE 84

refuse characteristics. However, as shown in Figure 84, the saturated permeability for milled refuse falls between 10^{-2} cm/sec. for the low density large particle refuse to 10^{-4} cm/sec. for high density small particle refuse.

To establish the validity of the field capacity determinations a moisture balance was performed on the various mini-lysimeter units. The total water applied to mini-lysimeters K through S is given in Table 24. The water was applied uniformly over an eighteen (18) month period and is equivalent to approximately twenty-seven (27) inches of infiltration. The total volume of leachate generated by each cylinder is also given in Table 24 along with the volume of water retained by the milled refuse. The original moisture content plus the water retained equals the actual milled refuse field capacity. These results are presented in Table 25.

A comparison of the field capacities determined by both procedures is made in Table 26. The field capacity values obtained from the moisture balance in the lysimeters is the actual field capacity that would be obtained by a refuse placed in an unsaturated condition. The comparison of results in Table 26 shows that the correlation between the experimental results obtained using the unsaturated test procedure and the mini-lysimeter is excellent.

A plot of field capacity versus D_{50} diameter for various milled refuse densities is presented in Figure 85. In Figure 86 is given a plot of time of first leachate appearance versus D_{50} diameter for two different compaction densities.

The results of this study indicate that milling of refuse increases greatly the saturated field capacity. Further, the results show that the field capacity of milled and unmilled refuse placed and compacted in an unsaturated state is less than the field capacity of refuse placed saturated.

These results also show that:

1. Increasing density increases field capacity. The increase in field capacity is nonlinear and approaches a limit as density increases.

2. As the D_{50} of the milled refuse decreases, the difference between saturated and unsaturated field capacity increases. This indicates that milling to finer sizes will increase the amount of refuse that will remain at a moisture content less than field capacity and will not be exposed to

TABLE 24

Moisture Balance in Lysimeters

Lysimeter	D_{50} mm.	Dry Density lbs/yd^3	Total Volume Water Added Liters	Total Volume Water Removed Liters	Volume Retained Liters
K	3.20	522.74	246.9	171.32	75.58
M	3.20	503.60	194.3	132.16	62.14
N	3.20	736.67	265.74	154.49	111.25
O	3.20	649.97	250.6	158.01	92.59
P	92.00	520.30	218.6	164.07	54.51
R	0.89	532.26	210.9	147.71	63.19
S	13.50	519.60	217.6	153.45	64.15

TABLE 25

Field Capacity Determination from Moisture Balance

Lysimeter	D_{50} mm.	Dry Density[a] lbs/yd^3	Water Retained Liters	Original Water Content in Liters	Total Water Liters	Field Capacities[a] In/ft.
K	3.20	522.74	75.58	10.97	86.55	5.75
M	3.20	503.60	62.14	10.97	73.11	4.70
N	3.20	736.67	111.25	17.33	128.58	7.36
O	3.20	649.97	92.59	14.29	106.88	6.87
P	92.00	520.30	54.51	11.05	65.56	3.95
R	0.89	532.26	63.19	6.06	69.26	3.68
S	13.50	519.60	64.15	11.10	75.27	4.54

[a] based on original refuse depth

TABLE 26

Comparison of Experimental and Calculated Field Capacity

Lysimeter	D_{50} mm.	Dry Density lbs/yd^3	Field Capacity Moisture Balance	Saturated Experiment[a]	Unsaturated Experiment[b]
K	3.20	522.74	5.75	8.2	5.5
M	3.20	503.60	4.70	8.1	4.4
N	3.20	736.67	7.36	9.2	6.2
O	3.20	649.97	6.87	8.8	6.0
P	92.00	520.30	3.95	4.0	4.0
R	0.89	532.26	3.68	9.1	4.6
S	13.50	519.60	4.54	5.8	4.9

a. from figure 83 Field Capacity vs. Density for Various Component Sizes (unsaturated samples)

b. from figure 82 Field Capacity vs. Density for Various Component Sizes (saturated samples)

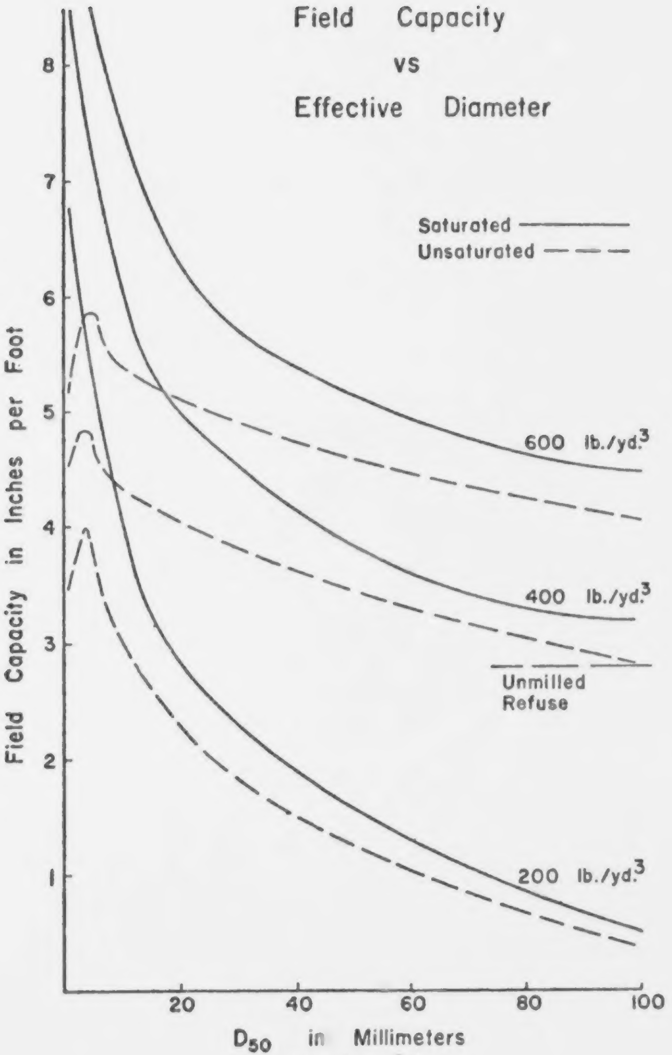

Field Capacity
vs
Effective Diameter
Saturated
Unsaturated
600 lb./yd.^{3}
400 lb./yd.^{3}
200 lb./yd.^{3}
Unmilled Refuse
Field Capacity in Inches per Foot
8
7
6
5
4
3
2
1
20
40
60
80
100
D_{50} in Millimeters

FIGURE 85

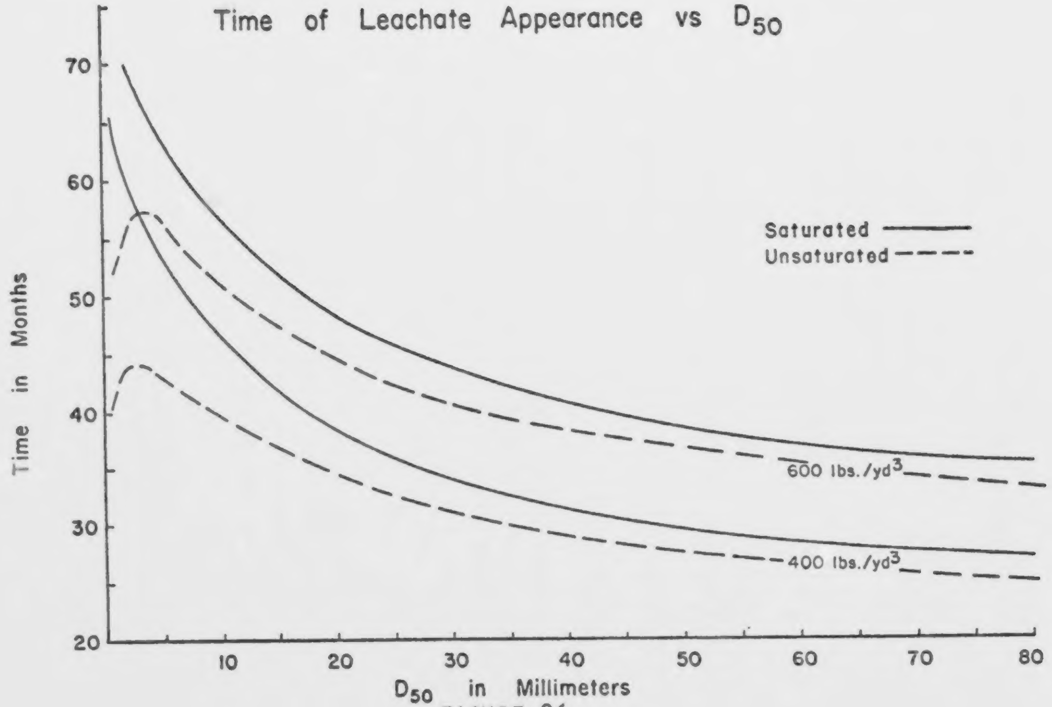

Time of Leachate Appearance vs D_{50}
Saturated
Unsaturated
600 lbs./yd^3
400 lbs./yd^3
Time in Months
70
60
50
40
30
20
10
20
30
40
50
60
70
80
D_{50} in Millimeters

FIGURE 86

the water flowing through the refuse. A possible result of this phenomenon would be quicker "apparent" stabilization of the refuse. The stabilization is only "apparent" because the leachate quality might show marked improvement yet the untouched pockets would retain their leachable load to be released at a slower rate or delayed to some future triggering.

The curve of first leachate appearance versus D_{50} diameter is presented in Figure 86. The model used for this figure was a landfill with an eight (8) foot (2.44 m.) refuse layer and a two (2) foot (0.61 m.)soil cover. Infiltration was assumed to be eighteen (18) inches (0.46 m.) per year. The independent variables considered were effective diameter (D_{50}) and refuse density. The results show that as the milled refuse size decreases, substantial delays in first leachate appearance will occur.

Using the unmilled refuse data from this study and elsewhere, a relationship between field capacity and density is

$$\text{Field Capacity} = 2.6\ (\ell n\ \text{Density}) - 14.0$$

Mini-Lysimeter Leachate

The quantity of leachate was essentially constant in all the mini-lysimeters, except M, because of the constant water feeding program. The maximum concentration of each pollutant measured is given in Table 27. Curves for the most significant pollutant concentrations are presented in Figures 87 through 96.

Figures 87 through 91 for mini-lysimeters K, P, R and S show the effect of refuse size on some of the leachate contaminant concentrations. Figures 92 through 96 show the effect of refuse density on the concentration of specific contaminents.

Plots of cumulative grams of pollutant as a function of leachate quantity are presented in Figures 97 through 104. The total grams of pollutant from each mini-lysimeter are tabulated in Table 28.

The effect of density on leachate ion concentrations are summarized in Table 29 and shown graphically in Figures 101 through 104. Three mini-lysimeter units were used to study density influence. Lysimeter K (D_{50} = 3.20 mm.) contained refuse at a density of 522 pounds/yard^3 (309.72 kgs per meter^3), lysimeter O (D_{50} = 3.20 mm.) contained refuse at a density of 650 pounds/yard^3 (385.67 kgs per meter^3) and lysimeter N (D_{50} = 3.20 mm.) contained refuse

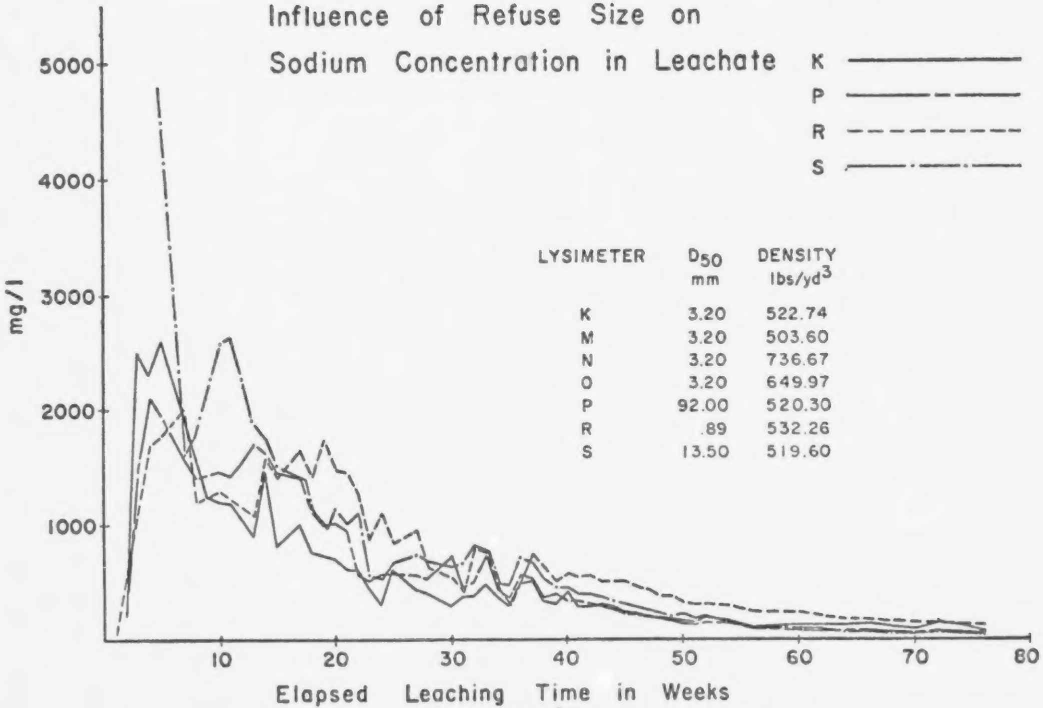
TABLE 27

Maximum Concentrations of Leachates from Lysimeters*

Mini-Lysimeters

Effective Size (D_{50} mm.)	3.20	3.20	3.20	3.20	92.00	0.89	13.50
	K	M	N	O	P	R	S
Iron	2130.74	1177.30	3,633	1,747	800.0	2,833	2341.0
Zinc	144.0	161.0	183.0	225.0	104.0	104.0	291.0
Nickel	1.52	1.71	3.14	3.43	1.83	1.63	2.22
Copper	0.19	0.21	0.26	0.29	0.26	0.71	0.29
Potassium	1,100	1,241	1,340	1,801	1,042	988	2,500
Calcium	1,640	3,983	3,840	2,602	1,825	1,940	2,400
Magnesium	381	950	759	794	306	389	1,276
Hardness	9,999.0	10,000	9,359	8,830	8,998	7,580	8,367
Chloride	2,500	4,550	2,890	3,700	2,390	2,190	4,800
Sodium	2,600	2,580	3,300	3,740	2,100	2,020	4,840
Ammonia Nitrogen	633.7	954.5	773.1	999.0	999.9	681.3	999.0
Organic Nitrogen	638.4	802.2	852.1	999.9	503.8	512.4	999.0
Chemical Oxygen Demand	50,749	58,800	95,304	78,000	55,000	51,000	93,900
Total Residue	36,760	59,000	49,580	69,330	33,460	26,180	76,640
TDS Total Dissolved Solids	18,000	22,500	22,500	26,100	17,000	16,000	35,000

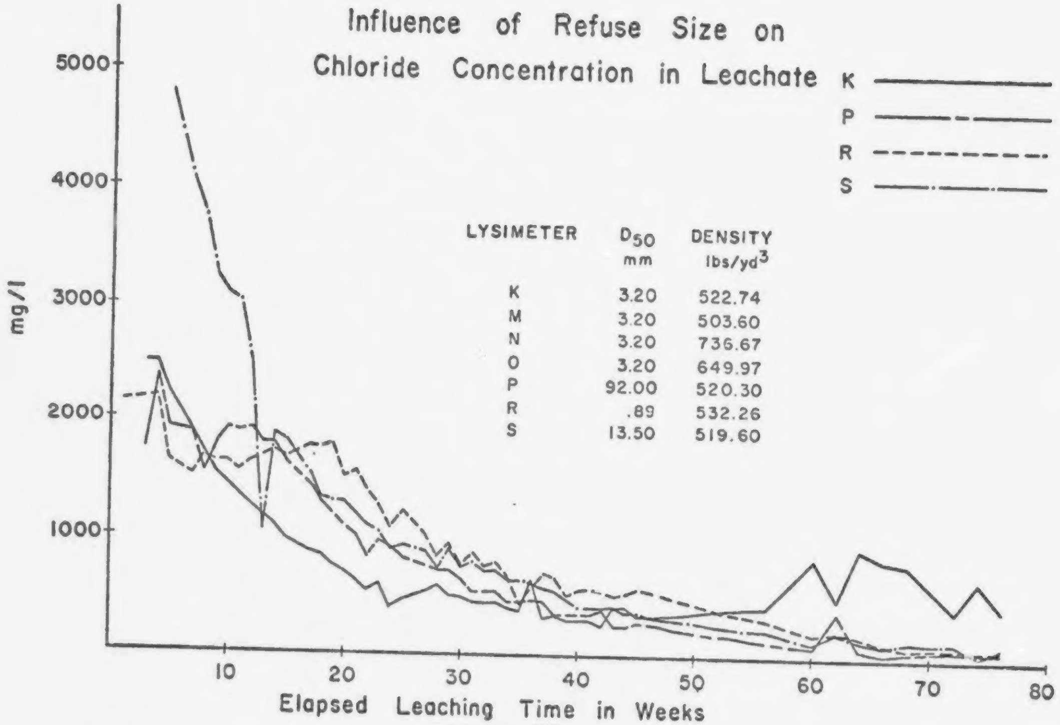
*milligrams per liter



Influence of Refuse Size on Sodium Concentration in Leachate

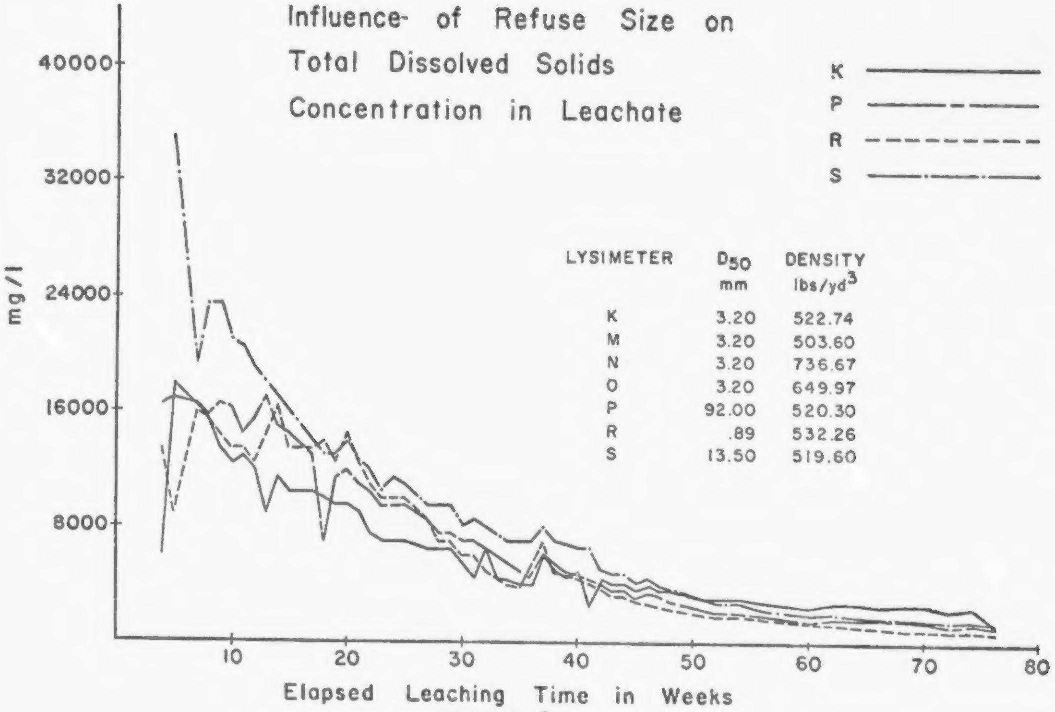
LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 87


Influence of Refuse Size on Chloride Concentration in Leachate

LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 88



LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 89

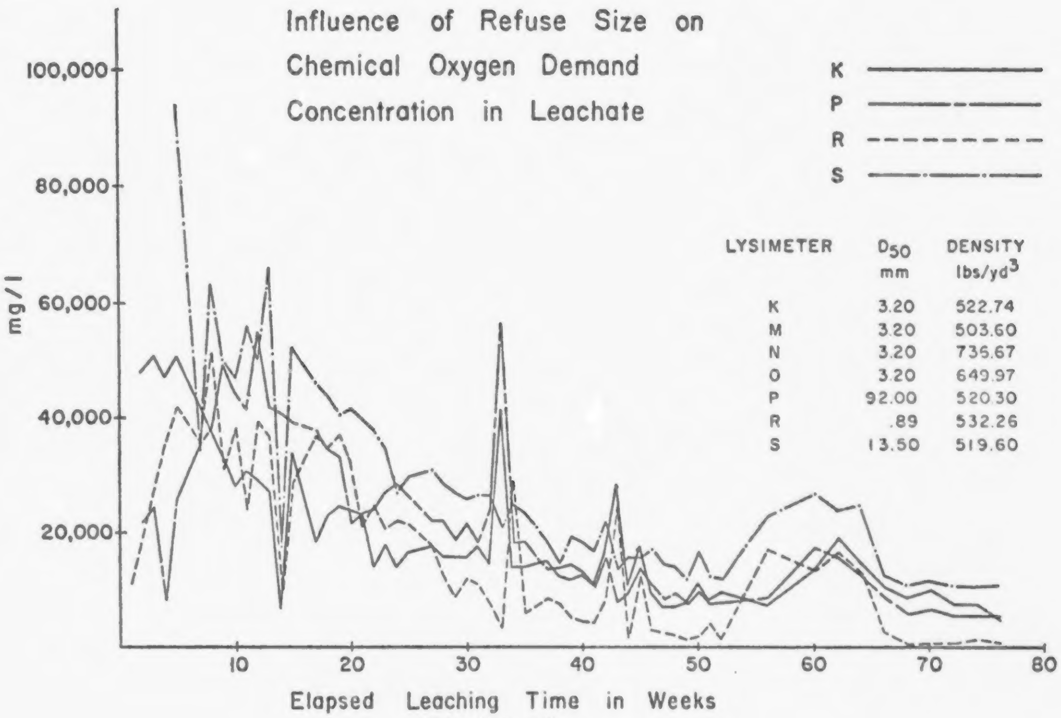
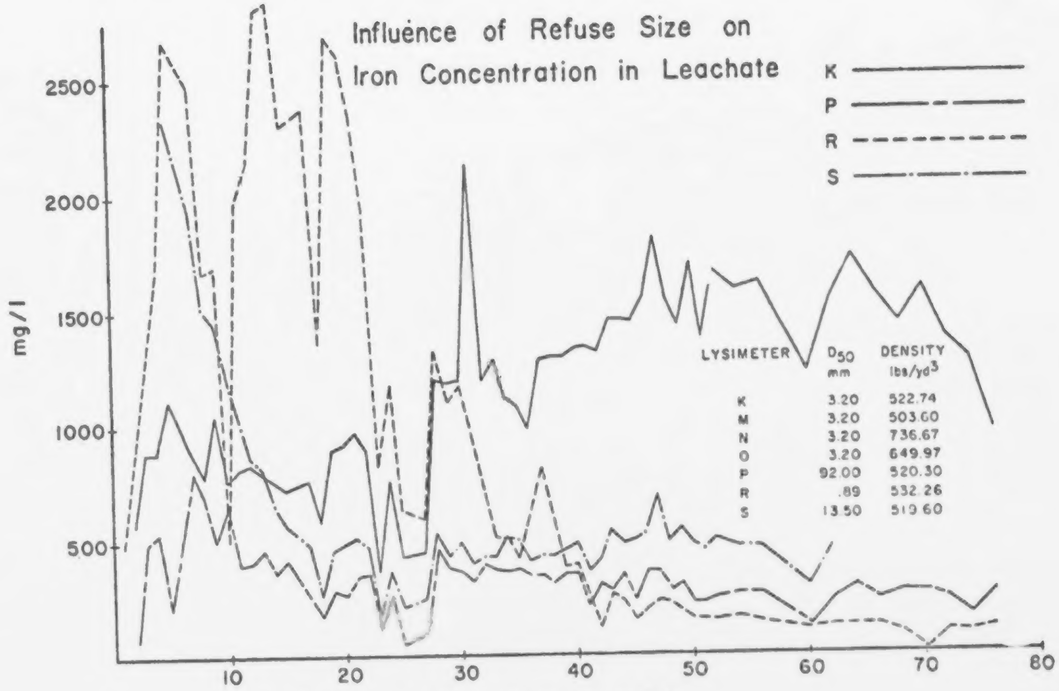
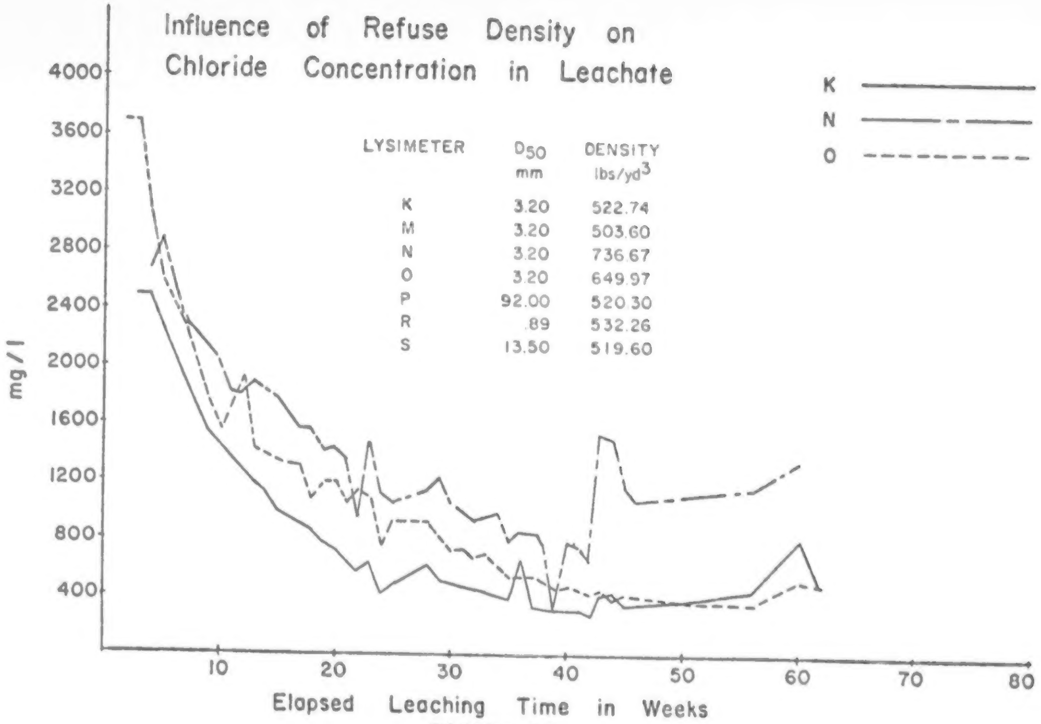

Influence of Refuse Size on
Chemical Oxygen Demand
Concentration in Leachate
K
P
R
S
LYSIMETER
D_{50} mm
DENSITY lbs/yd^3
K 3.20 522.74
M 3.20 503.60
N 3.20 736.67
O 3.20 649.97
P 92.00 520.30
R .89 532.26
S 13.50 519.60
100,000
80,000
60,000
40,000
20,000
mg/l
10
20
30
40
50
60
70
80
Elapsed Leaching Time in Weeks

FIGURE 90



LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

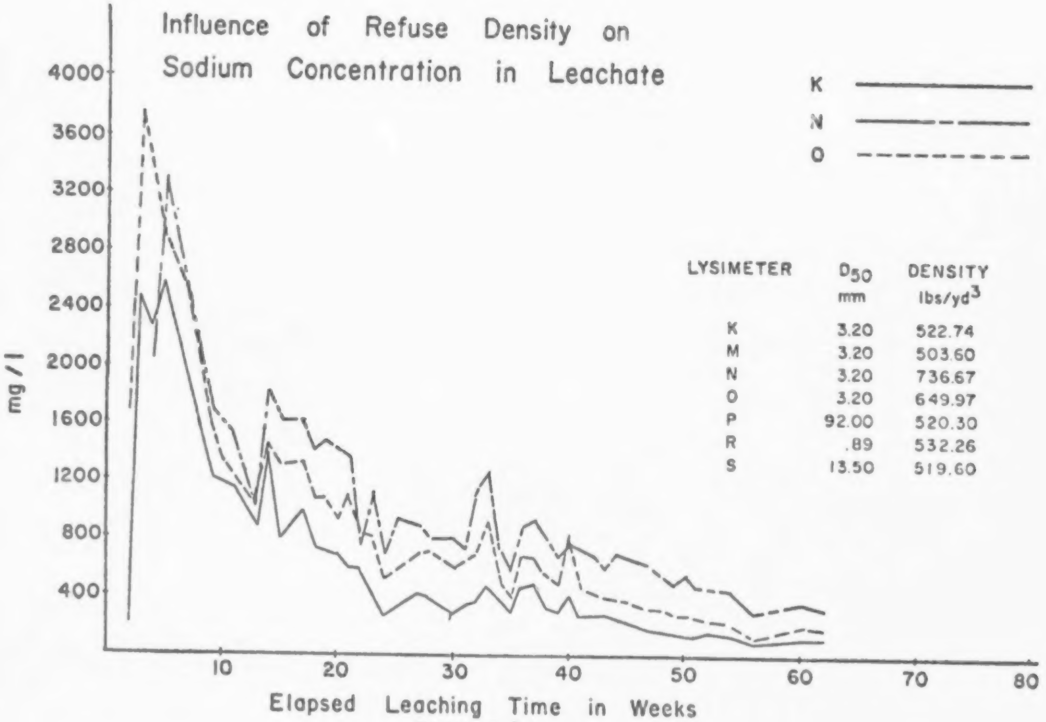
FIGURE 91



Influence of Refuse Density on Chloride Concentration in Leachate

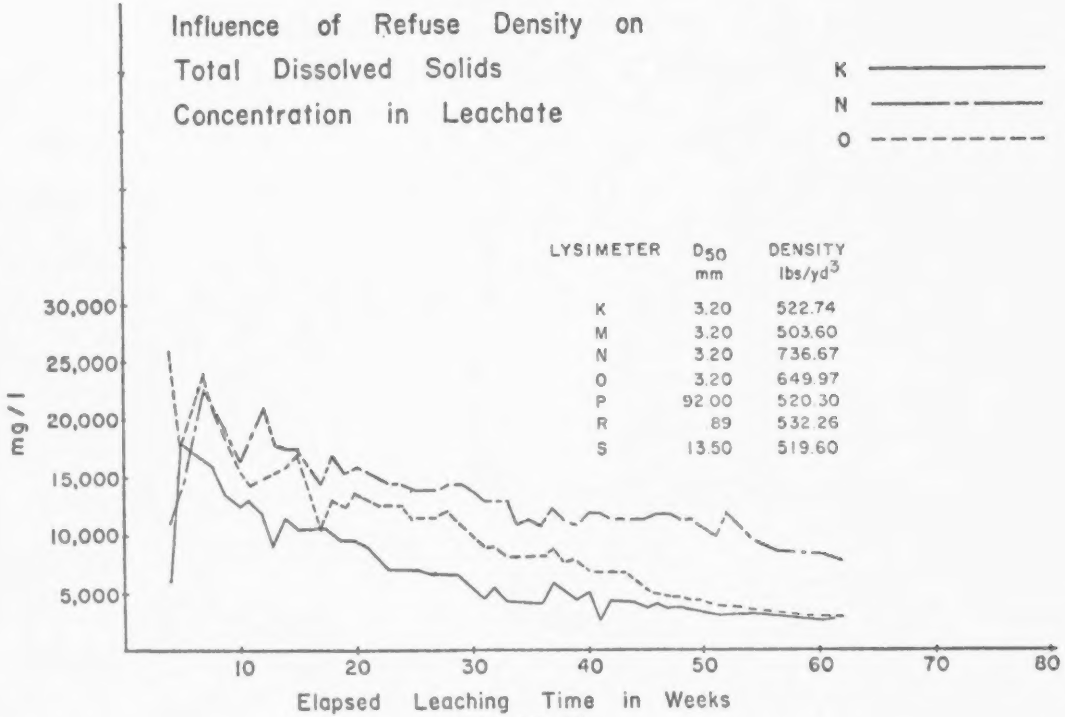
LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 92



LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 93



LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	89	532.26
S	13.50	519.60

FIGURE 94

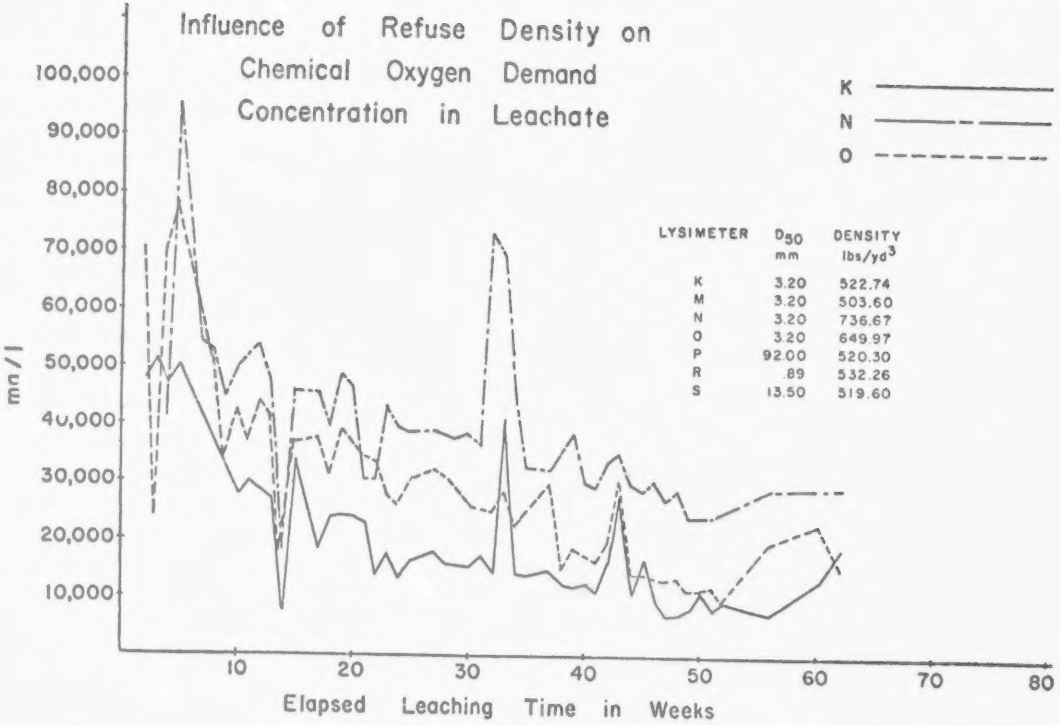

Influence of Refuse Density on
Chemical Oxygen Demand
Concentration in Leachate
K
N
O
LYSIMETER
D_{50} mm
DENSITY lbs/yd^3
K 3.20 522.74
M 3.20 503.60
N 3.20 736.67
O 3.20 649.97
P 92.00 520.30
R .89 532.26
S 13.50 519.60
mg/l
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
10
20
30
40
50
60
70
80
Elapsed Leaching Time in Weeks

FIGURE 95

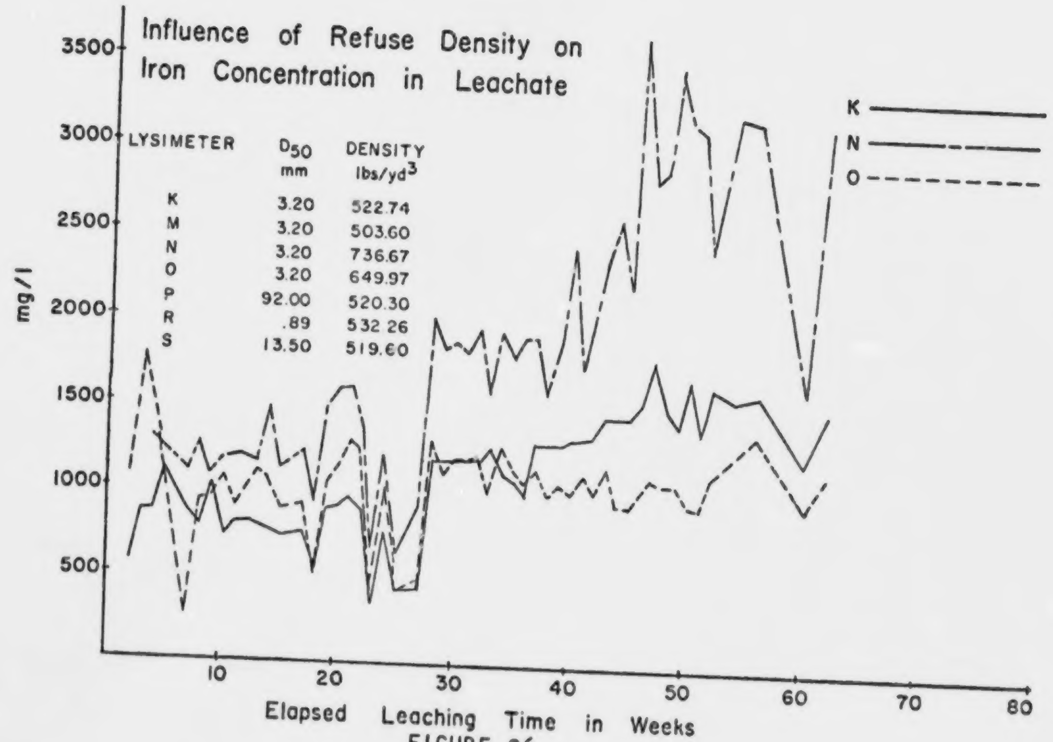
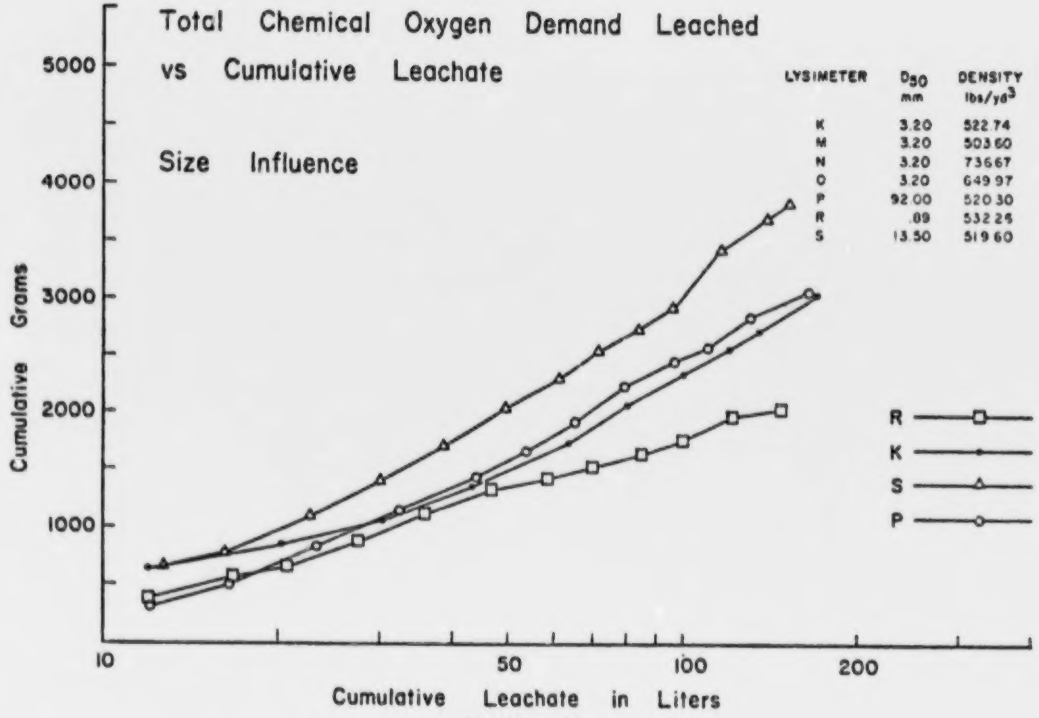

Influence of Refuse Density on Iron Concentration in Leachate
LYSIMETER
D50 mm
DENSITY lbs/yd3
K 3.20 522.74
M 3.20 503.60
N 3.20 736.67
O 3.20 649.97
P 92.00 520.30
R .89 532.26
S 13.50 519.60
mg/l
3500
3000
2500
2000
1500
1000
500
10
20
30
40
50
60
70
80
Elapsed Leaching Time in Weeks
K
N
O

FIGURE 96

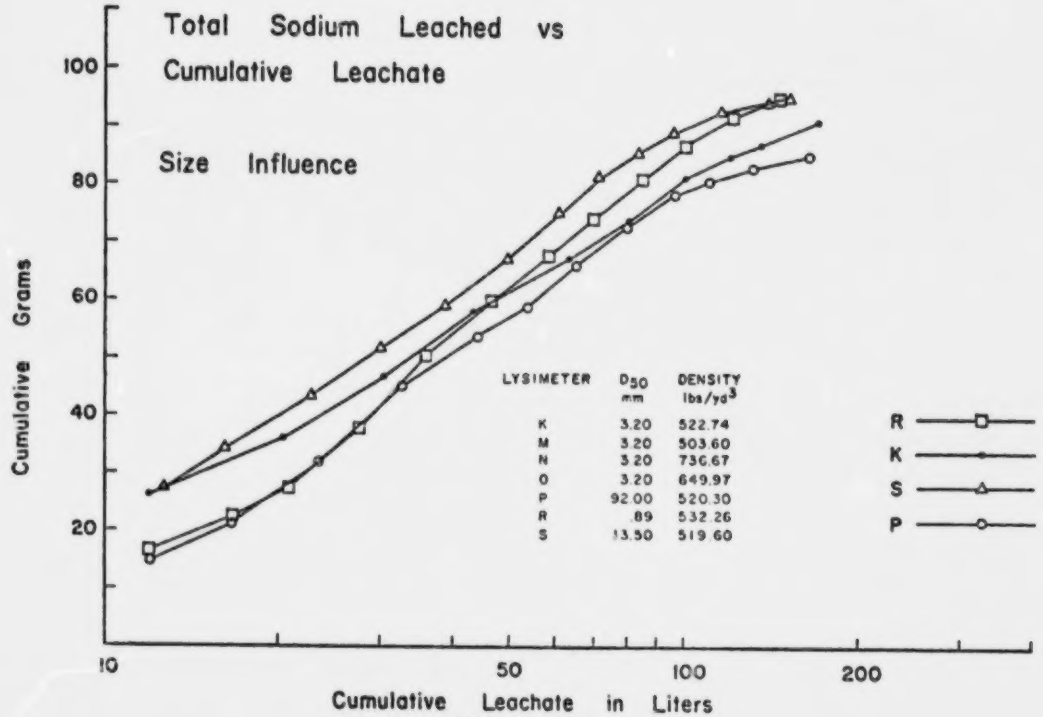


Total Chemical Oxygen Demand Leached vs Cumulative Leachate

Size Influence

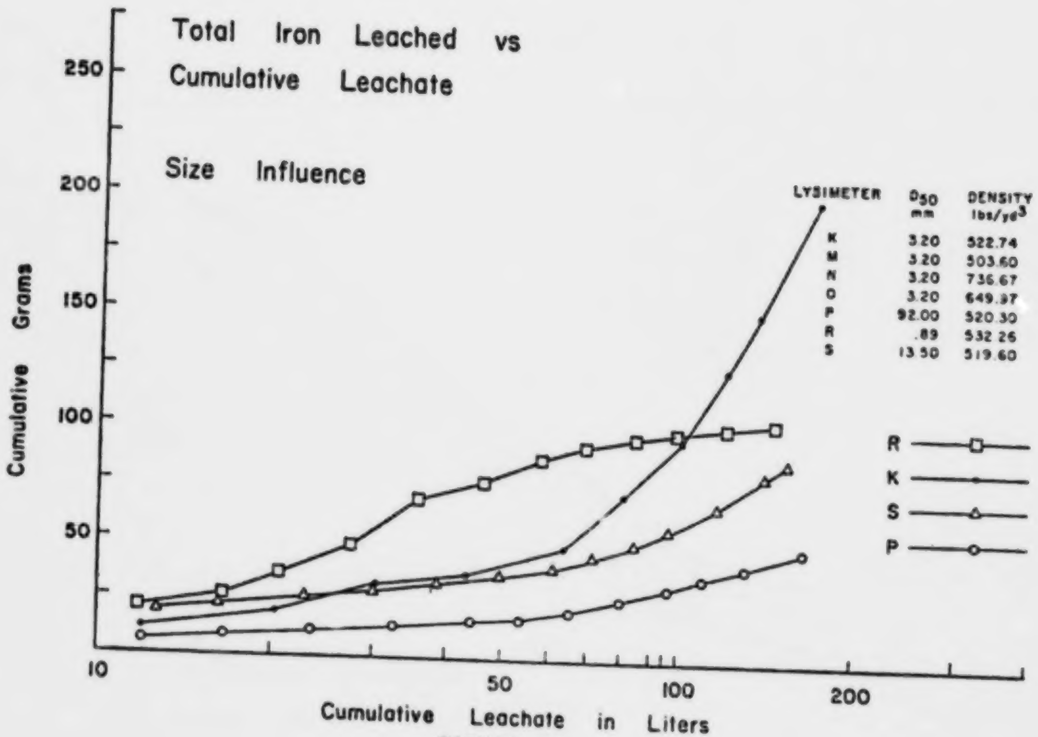
LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.09	532.25
S	13.50	519.60

FIGURE 97



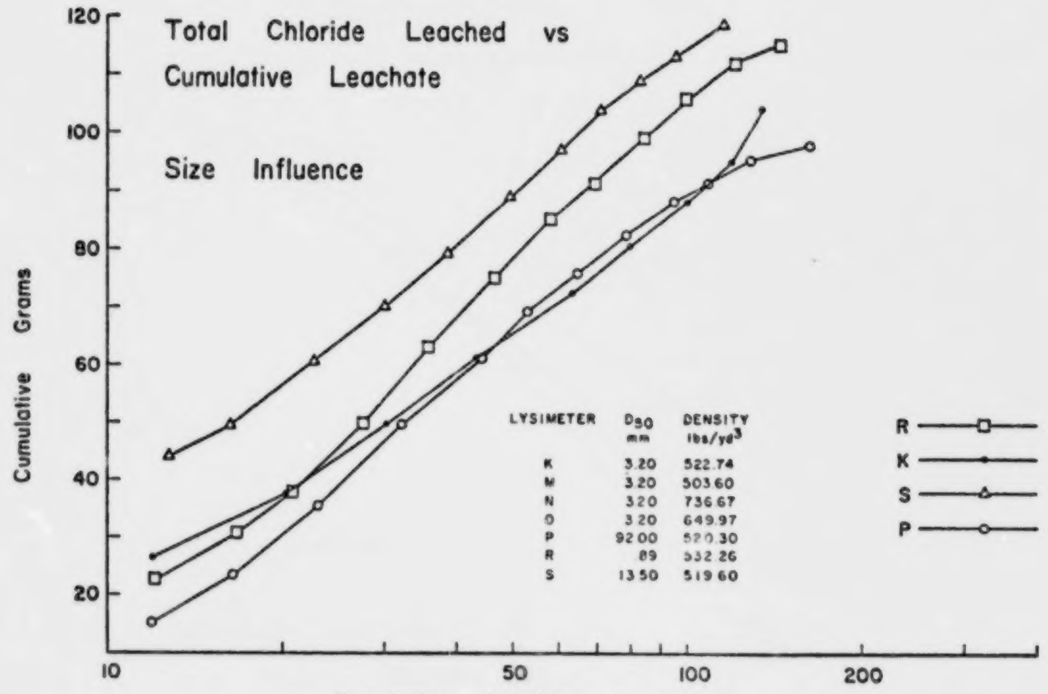
LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 98



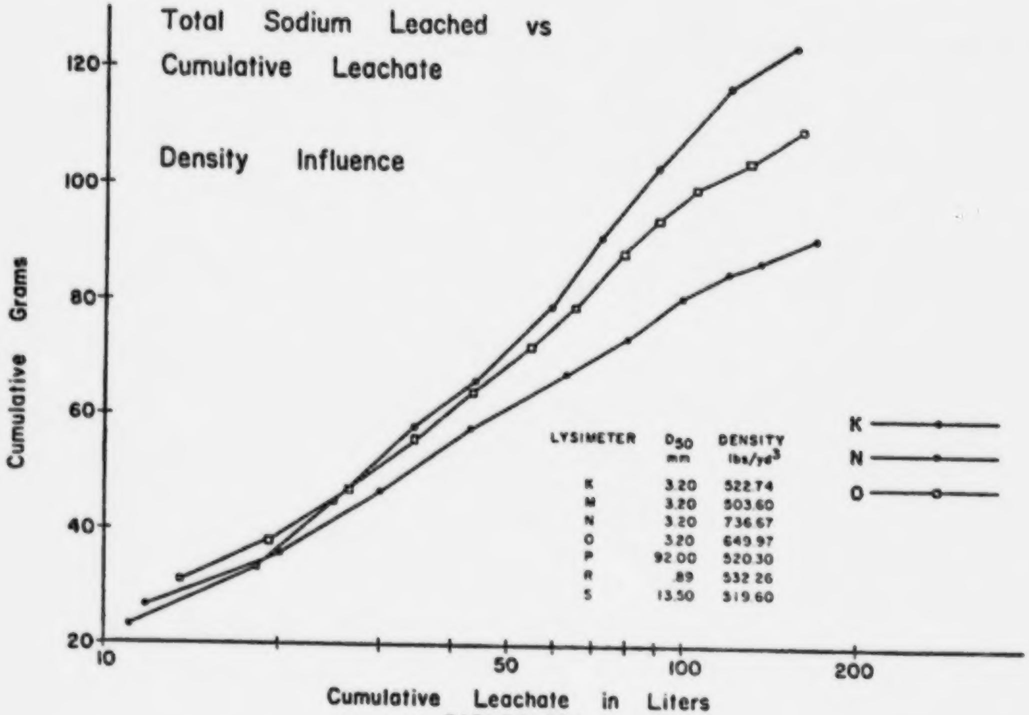
LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.37
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 99



LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 100

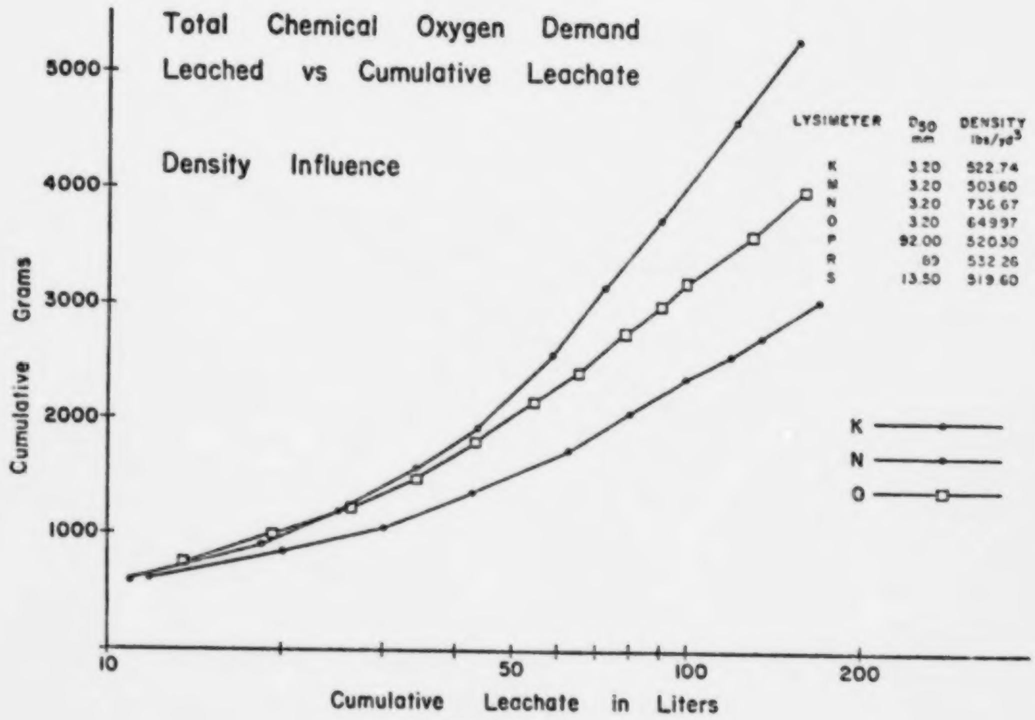


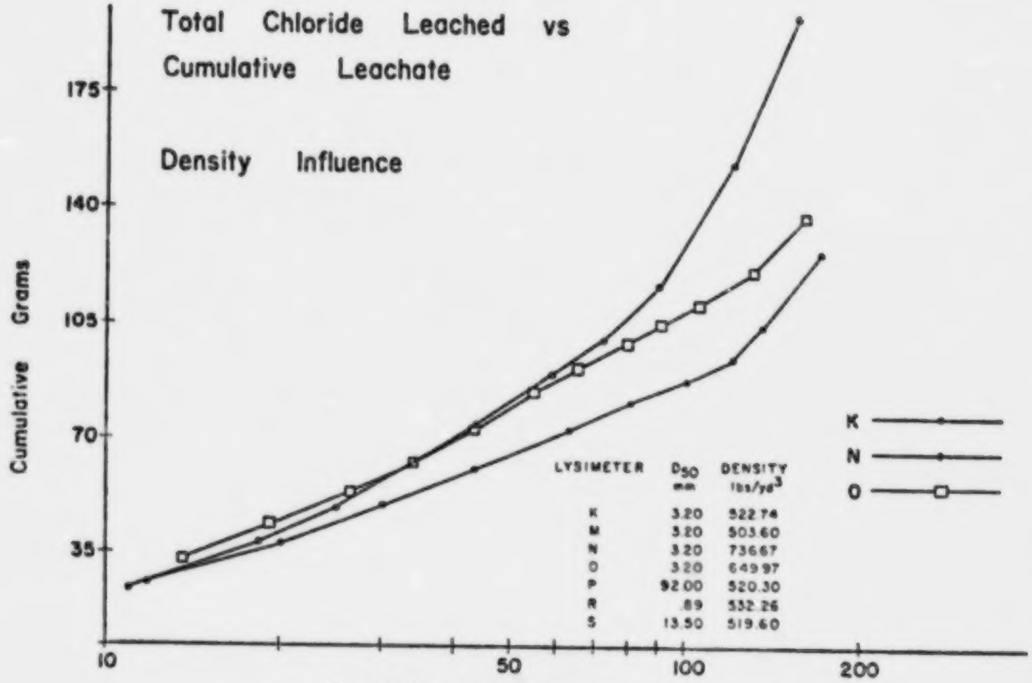
Total Sodium Leached vs Cumulative Leachate

Density Influence

LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

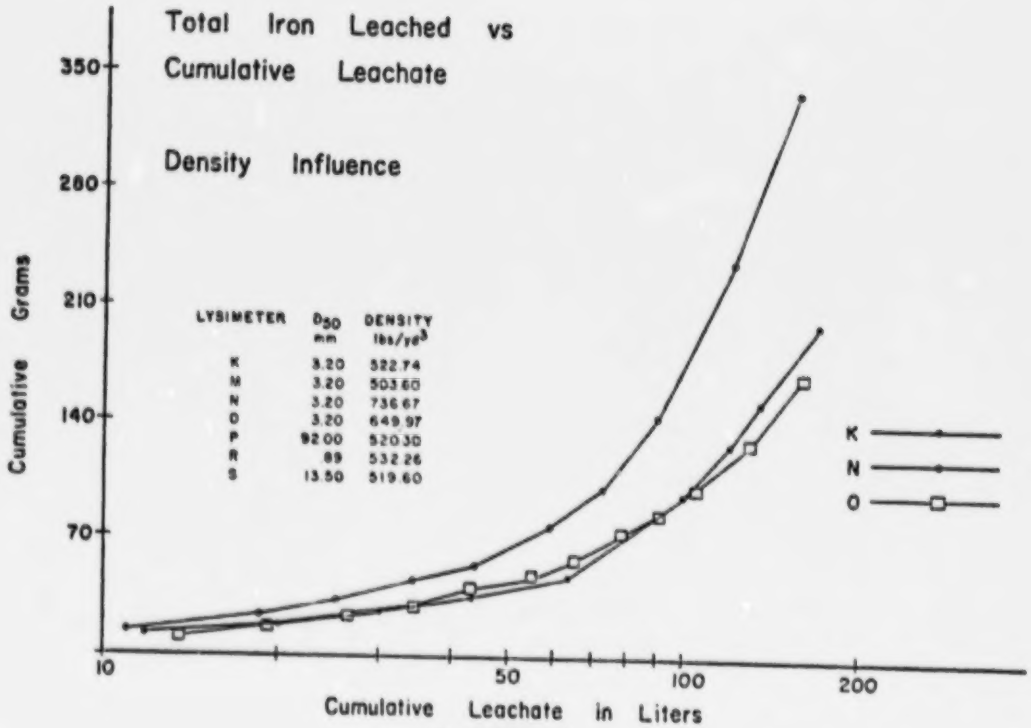
FIGURE 101





LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	.89	532.26
S	13.50	519.60

FIGURE 103



Total Iron Leached vs Cumulative Leachate

Density Influence

LYSIMETER	D_{50} mm	DENSITY lbs/yd^3
K	3.20	522.74
M	3.20	503.60
N	3.20	736.67
O	3.20	649.97
P	92.00	520.30
R	89	532.26
S	13.50	519.60

FIGURE 104

TABLE 28

Total Grams of Pollutant Removed From Each Lysimeter

	Lysimeter						
	K	M	N	O	P	R	S
Hardness	469.0	486.7	623.1	529.1	364.8	213.1	379.5
Sodium	91.0	98.3	123.8	109.7	85.0	95.0	94.6
Iron	200.12	95.01	345.14	169.56	48.83	103.9	86.65
Zinc	3.34	2.90	9.38	4,87	4.76	1.72	4.38
Nickel	0.07	0.07	0.12	0.09	0.09	0.05	0.07
Copper	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PO_4	0.1	0.7	0.30	0.2	0.8	0.00	0.6
SO_4	33.5	20.1	13.6	19.1	12.6	17.2	8.1
Cl	127.2	121.3	199.1	138.8	97.9	114.9	122.8
SS	90.2	92.7	177.7	113.7	59.4	53.3	42.3
N Free	33.2	44.2	56.7	61.8	42.7	27.1	45.2
N Or.	18.1	18.9	28.4	23.3	21.0	17.7	30.7
COD	3,063.7	2,726.4	5,291.0	3,974.4	3,094.3	2,021.1	3,851.7
K	44.6	43.9	58.5	61.5	46.6	42.9	69.1
Ca	122.0	136.1	227.0	169.2	129.8	61.3	149.2
TDS	1,013.3	1,112.1	1,804.8	1,390.5	1,023.6	843.0	1,150.5
Leachate	171.32	132.16	154.49	158.01	164.07	147.71	153.45
Weight (lbs.)	146.89	146.05	232.05	189.14	148.07	157.55	148.58
Volume (yd^3)	.281	.290	.315	.291	.285	.296	.286
Density (lbs/yd^3)	522.74	503.6	736.67	649.97	520.3	532.26	519.6
Height (orig. ft.)	2.4	2.5	2.709	2.50	2.491	2.542	2.494
Height (final ft.)	2.042	1.834	2.583	2.25	2.229	1.750	2.234

TABLE 29

EFFECT OF MILLED REFUSE DENSITY ON REMOVAL OF POLLUTANTS[a]

	K(522)[b]	O(650)[b]	N(722)[b]
Hardness	18.64	17.70	17.38
Sodium	3.62	3.67	3.45
Iron	7.95	5.67	9.63
Zinc	.132	.162	.26
Nickel	.002	.003	.003
Copper	0.0	0.0	0.0
PO_4	.003	.006	.008
SO_4	.331	.639	.38
Cl	5.05	4.64	5.55
SS	3.58	3.80	4.96
N Free	1.32	2.06	1.58
N Or	.72	.78	.79
COD	121.74	132.99	147.59
K	1.77	2.05	1.63
Ca	4.85	5.66	6.33
TDS	40.27	46.53	50.34

a. Removal per pound of refuse per liter of leachate
b. Minilysimeter (density in pounds/cu.yd.)

at a density of 737 pounds/yard^3 (437.29 kgs per meter^3).

The results show that pollutant concentrations increased with increasing density. Lysimeter N leachate had the highest weekly pollutant load in at least 90% of the study period. Lysimeter K leachate had the lowest concentrations of pollutant in at least 75 percent of the report period.

The results show the increased availability of pollutants as refuse density increases. Hence, as long as the pollutant does not reach its solubility limit in the leachate, more will be removed during a given time period. In this study this solubility limit (saturation) was not reached.

The water feeding program produced leachates which were rich in both organic and inorganic contaminents. In most cases the maximum concentrations of pollutants were attained within the first two months of the test initiation. After the maximum concentrations were reached, a continual decrease occurred in leachate from all the constant feed mini-lysimeters. The steady decrease was produced by the continued flushing of the refuse, thereby removing the easily decomposable and soluble materials.

The rate of removal of the bound contaminents depends on their rate of release due to biochemical activity within the refuse. The refuse size concentration curves, Figures 87 through 91, show that except for early transients size does not appear to have any significant influence on concentrations.

Iron does not appear to follow the general trend in the same orderly fashion. The moderate size refuse (D_{50} = 3.20 mm.) increased in iron concentration and stayed there until test termination. The reason for this pattern difference has not been established.

SANITARY LANDFILL FIELD FACILITY

Background ground water quality data was collected at the site prior to installation of the test cell in the Spring of 1968. Complete ground water background data for wells 1 through 11 are summarized in the data volumes of the earlier report on this study(4). Wells 1 through 11 fall outside the test cell, while wells 12 and 13 are within the cell and had to be installed after its construction. Concentration ranges for wells 1 through 11 for the various contaminants measured are summarized in Table 30.

Overall ground water quality was good with only low concentrations of the various contaminants present.

TABLE 30

FIELD FACILITY LEACHATE CHEMICAL COMPOSITION SUMMARY FOR WELLS 1 THROUGH 11 AND 14

mg/ℓ (EXCEPT pH)

ION	for Test Period	Typical Concentration on Indicated Dates			
		9/11/69 (background)	8/31/70	8/2/71	6/26/72
Iron	2.30	0.0	0.73	0.61	1.64
Zinc	1.73	0.03	0.37	0.10	0.13
Nickel	0.23	0.0	0.0	0.0	NR
Copper	0.22	0.0	0.0	0.0	NR
pH (range)	2.8-8.2	5.0	6.4	6.5	6.7
Hardness ($CaCO_3$)	112.0	30.0	37.0	35.0	NR
Phosphate	1.7	0.2	0.2	0.0	0.0
Sulfate	22.0	2.0	0.0	NR	NR
Chloride	50.0	10.0	9.0	18.0	23.0
Sodium	48.0	6.0	6.0	7.0	4.0
Nitrogen (ammonia)	1.0	0.0	0.0	0.1	0.0
Nitrogen (organic)	1.4	0.4	0.1	0.1	0.1
Total Dissolved Solids	330.0*	60.0	65.0	70.0	80.0
Chemical Oxygen Demand	177.0*	0.0	3.0	0.0	40.0

NR - not reported

* Isolated results.

Refuse was placed in the field test cell in May 1968. After that time, gas, soil moisture, ground water samples and temperatures were monitored on a regular basis.

Field Temperature

Figure 105 is taken from the first report on this project(4) and shows the temperature variations during the time period immediately after installation of the field cell. These results and those summarized in Table 31 are the average of the four (4) thermistors at each depth. The two foot (.61 m.) depth curve shows maximum response to atmospheric temperatures. The curves for the other depths indicate that during the reported time period internal temperatures had a highly dampened phase response to atmospheric and ground temperatures. The results indicate very little initial biological activity within the refuse (as compared to the lysimeter). It is believed that the initial temperature behavior pattern is a result of the relatively high refuse placement density (740 lbs/yd^3) (439.1 kgs/meter^3).

After the initial time period temperature patterns continue to follow trends similar to those shown in Figure 105. Hence, complete curves for the entire test period are not presented. In Table 31 are summarized temperature ranges for each depth and for each year of test cell monitoring. The results show that temperatures inside the fill are higher than those at corresponding depths outside the fill and a few degrees above ambient. It is also noteworthy that in the test cell at the greater depths a cooling trend toward exterior temperatures is apparent with each annual cycle.

Overall, the temperature measurements in the test cell provide little insight into its state of decomposition.

Field Gas

Gas samples were analyzed on a routine basis for carbon monoxide, hydrogen sulfide, nitrogen, carbon dioxide and methane. No carbon monoxide or hydrogen sulfide was detected. The gas curves in Figures 106 through 125 for oxygen, carbon dioxide and methane are presented as a percentage of total gas present at the time of sampling. Nitrogen, which made up the remaining percentage of the total is not shown in the figures.

The "A" series and "D" series gas curves are for locations outside the test area. The results show that while there are variations in carbon dioxide and oxygen, negligible quantities of methane were detected. A comparison between

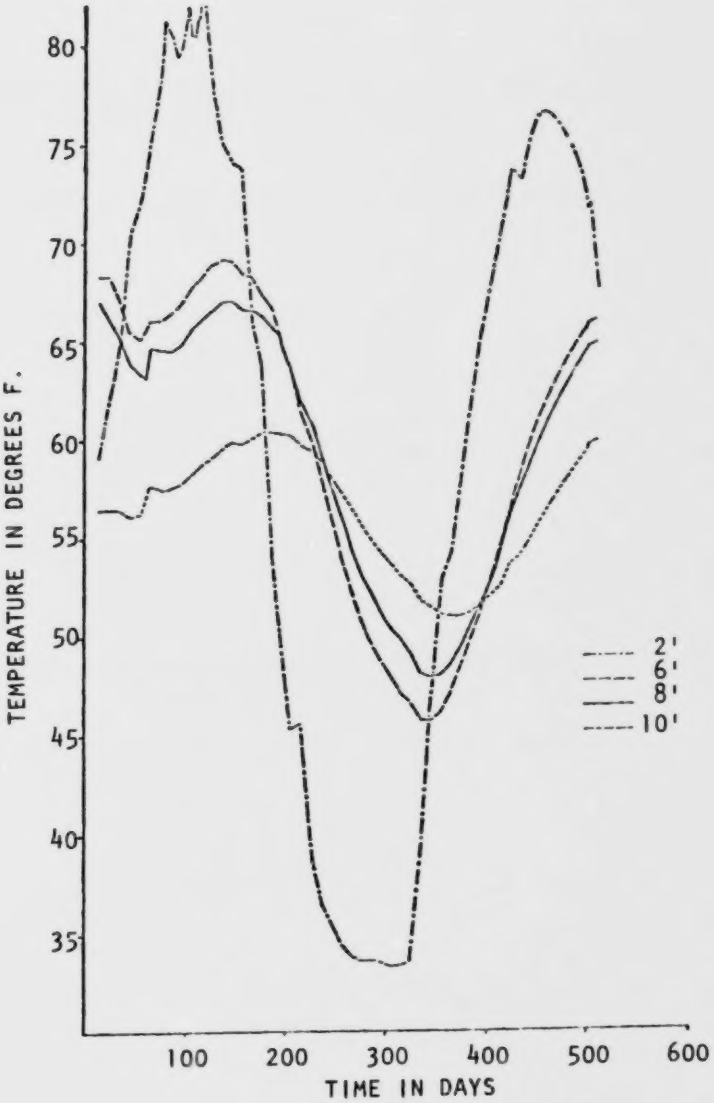


FIGURE 105
FIELD TEMPERATURES

TABLE 31

Field Facility Temperature Extremes Outside the Fill Area[a]

Depth Below Ground Surface - Feet

	.5	5	8	13	18
From 9/1/69 to 8/31/70					
Maximum	106.0	69.5	62.5	58.9	55.0
Minimum	24.1	37.5	44.0	46.5	50.5
From 9/1/70 to 8/31/71					
Maximum	95.0	69.3	62.7	58.8	56.0
Minimum	19.0	35.0	40.0	47.5	48.5
From 9/1/71 to 7/15/72					
Maximum	93.8	69.0	62.4	58.5	56.5
Minimum	22.0	36.6	42.0	45.5	47.9

Field Facility Temperature Extremes Inside the Fill Area[a]

Depth Below Ground Surface - Feet

	2	4	6	8	10	12
From 9/1/69 to 8/31/70						
Maximum	75.5	71.0	66.5	64.5	59.0	59.0
Minimum	34.0	39.0	44.5	46.5	49.0	50.9
From 8/31/70 to 8/31/71						
Maximum	75.0	68.8	64.9	64.0	58.5	57.7
Minimum	32.0	36.0	41.5	41.5	46.0	47.0
From 9/1/71 to 7/15/72						
Maximum	74.9	69.8	64.4	64.1	58.8	58.7
Minimum	33.3	37.8	40.5	43.3	46.2	49.9

[a] Fahrenheit

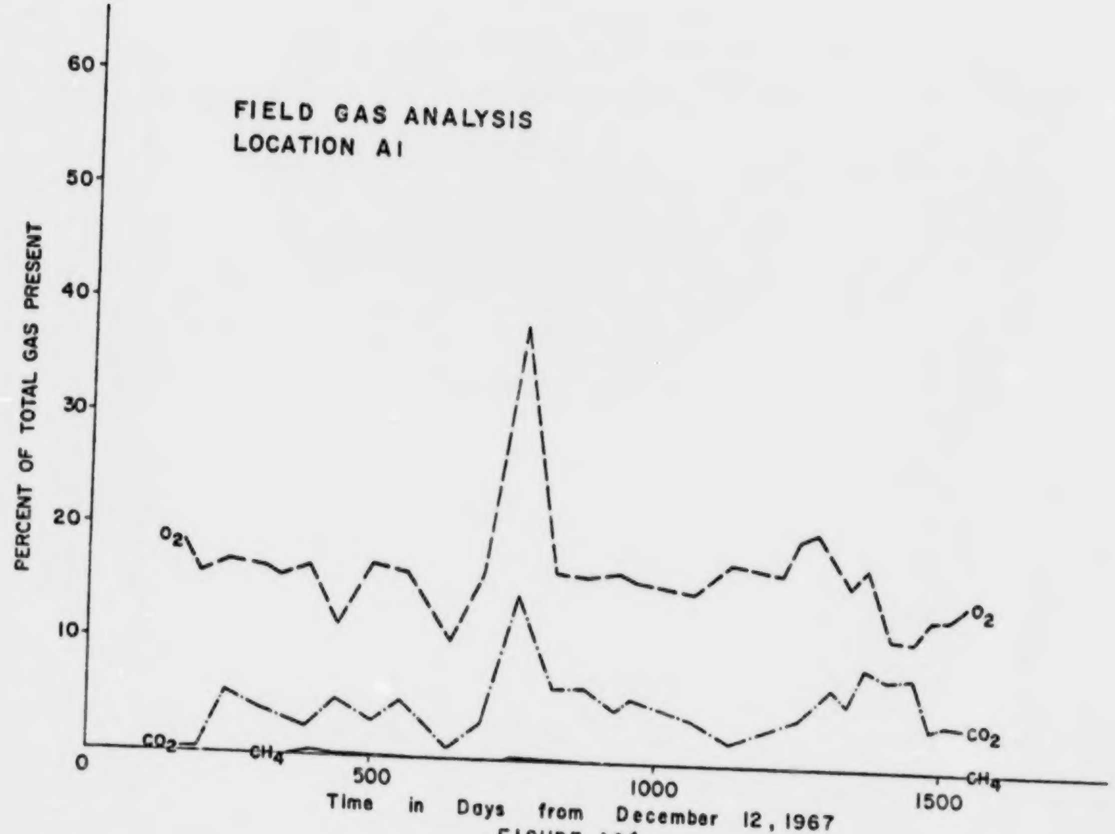

FIELD GAS ANALYSIS
LOCATION A1
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
O_2
CO_2
CH_4
O_2
CO_2
CH_4

FIGURE 106

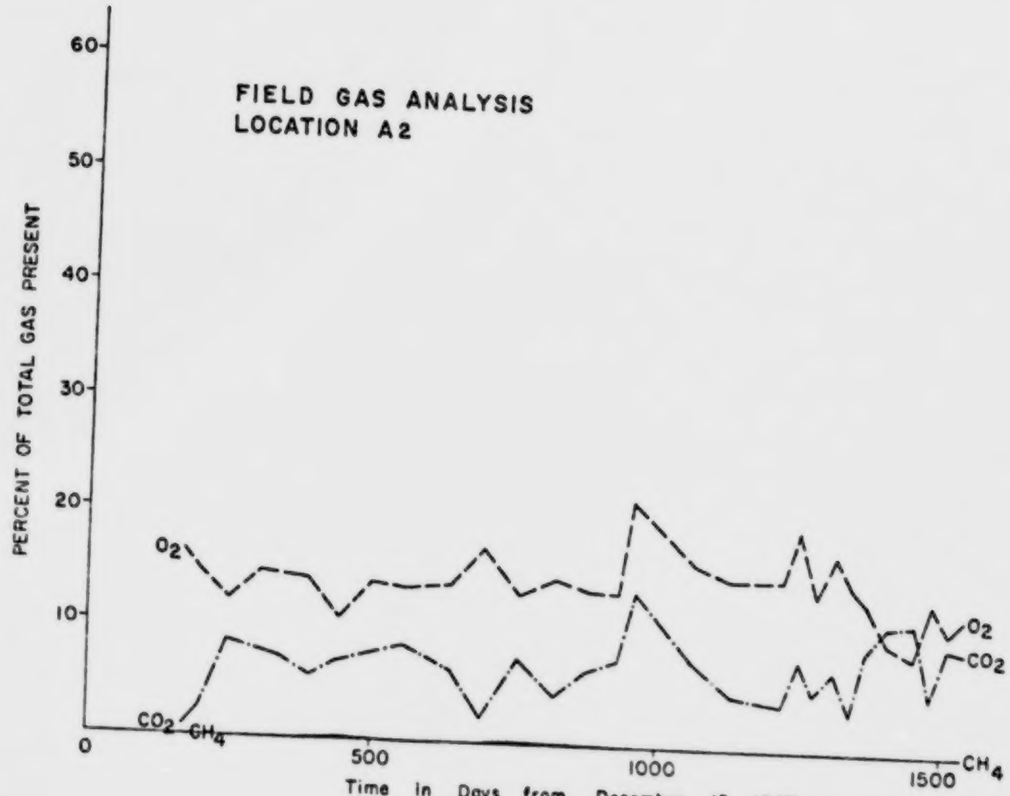

FIELD GAS ANALYSIS
LOCATION A2
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
O_2
CO_2
CH_4
O_2
CO_2
CH_4

FIGURE 107

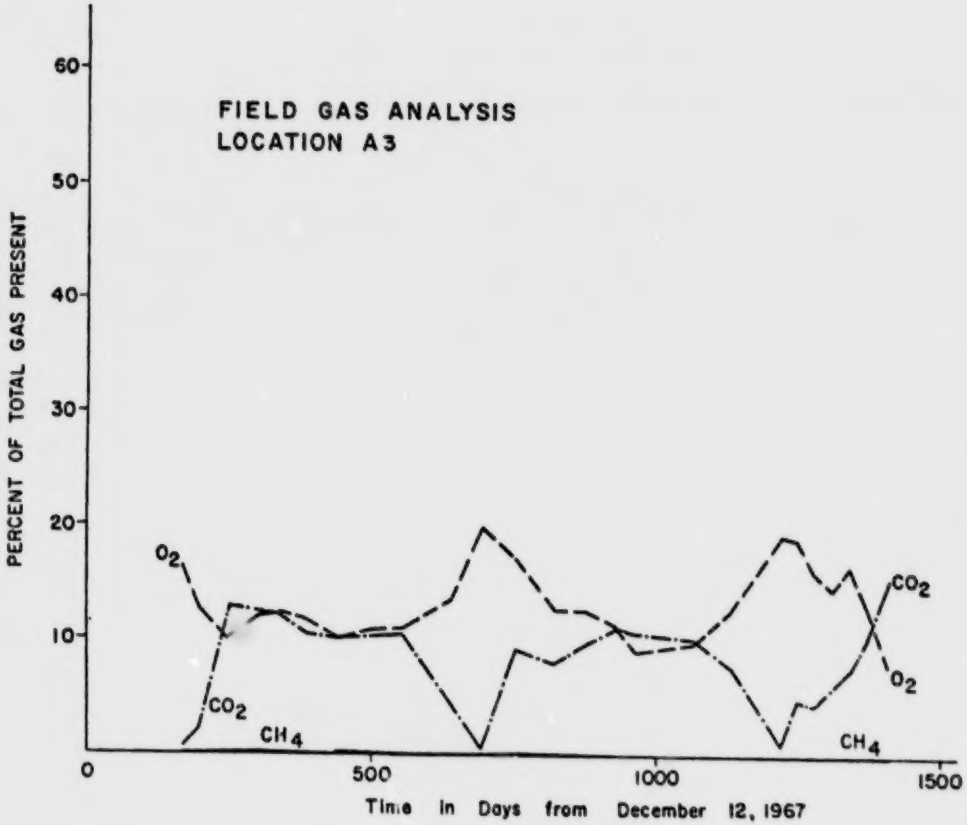

FIELD GAS ANALYSIS
LOCATION A3
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
O_2
CO_2
CH_4
CO_2
O_2
CH_4

FIGURE 108

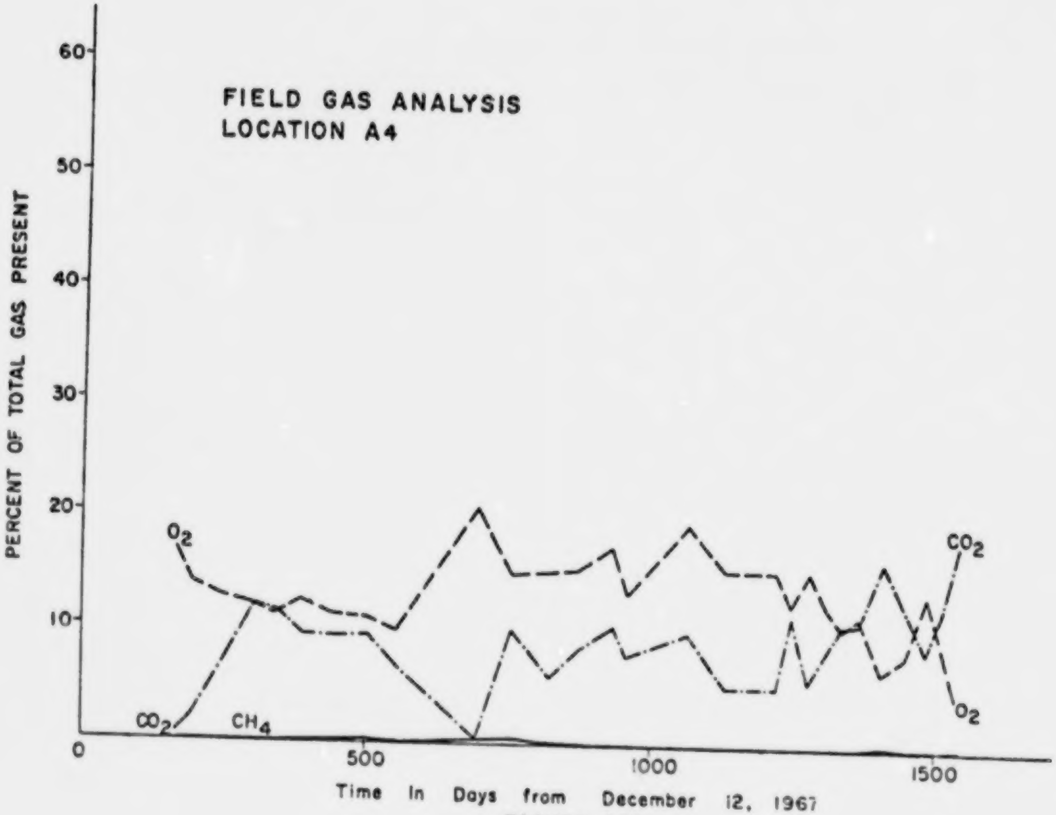

FIELD GAS ANALYSIS
LOCATION A4
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time In Days from December 12, 1967
O_2
CO_2
CH_4
CO_2
O_2

FIGURE 109

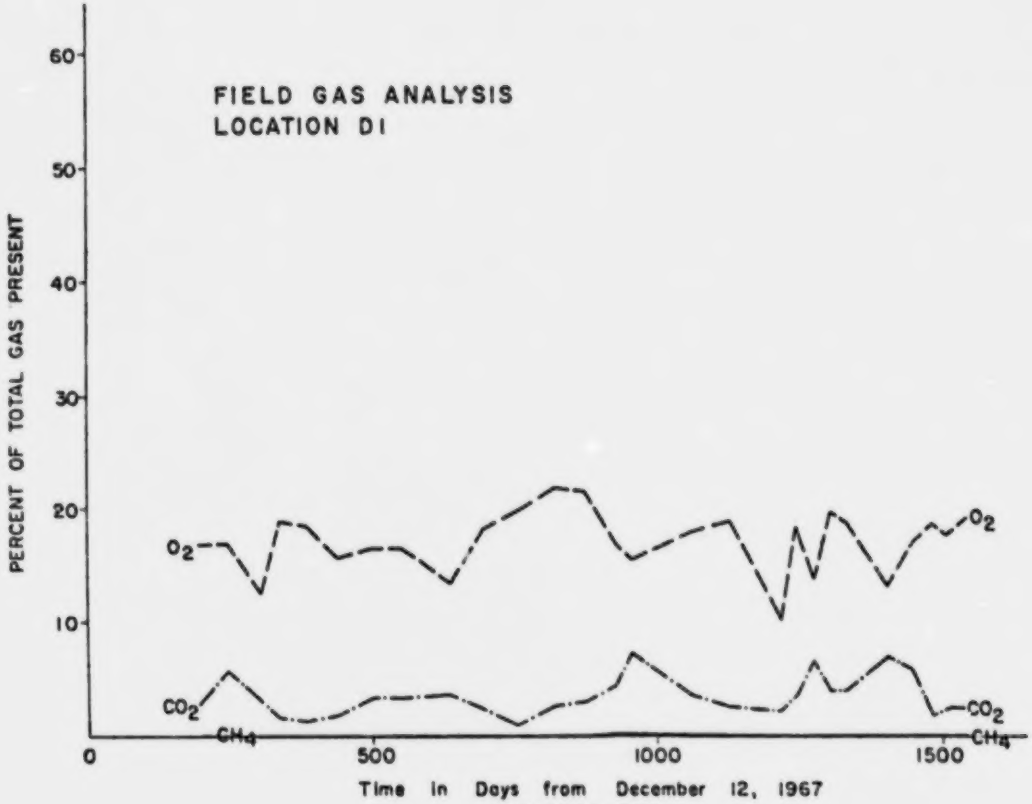

FIELD GAS ANALYSIS
LOCATION D1
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
O_2
O_2
CO_2
CO_2
CH_4
CH_4

FIGURE 110

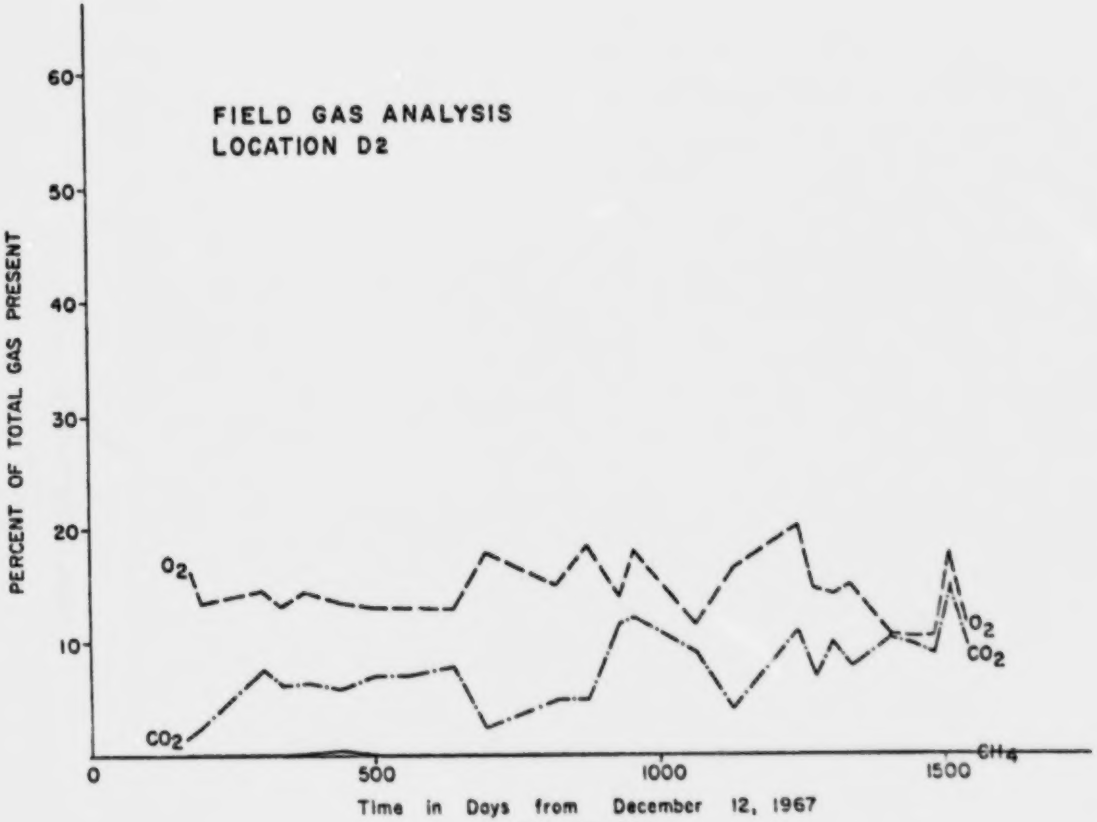

FIELD GAS ANALYSIS
LOCATION D2
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
O_2
CO_2
O_2
CO_2
CH_4

FIGURE 111

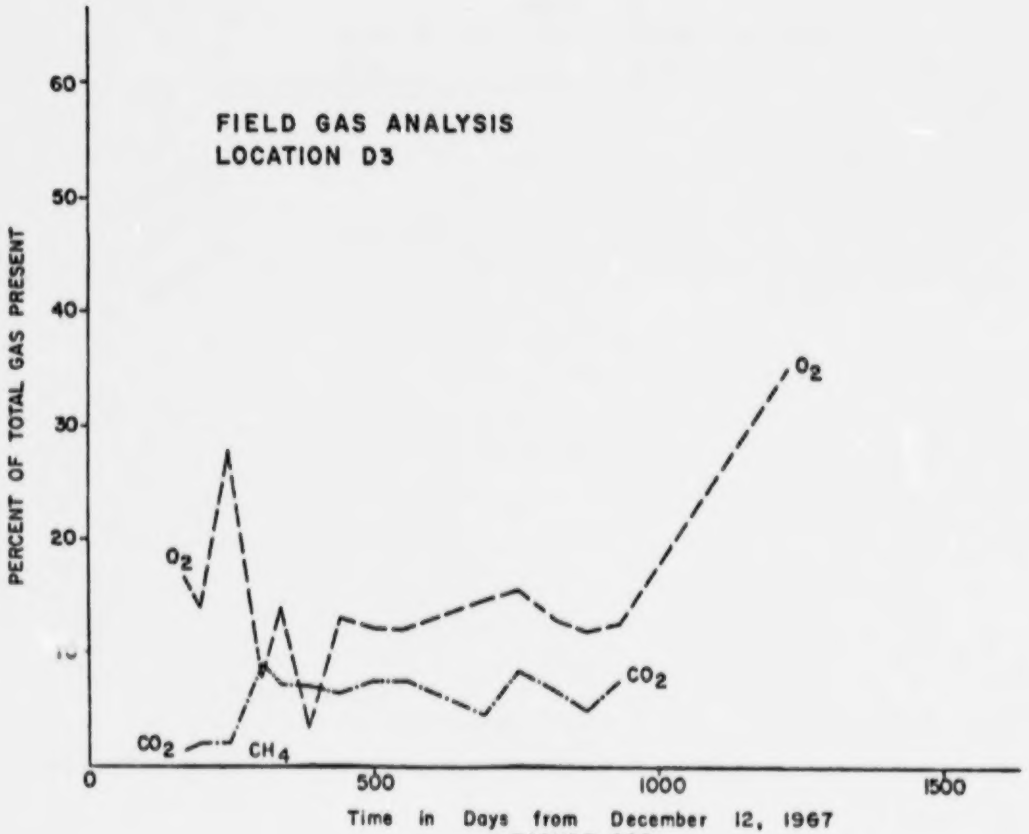

FIELD GAS ANALYSIS
LOCATION D3
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
O_2
O_2
CO_2
CO_2
CH_4

FIGURE 112

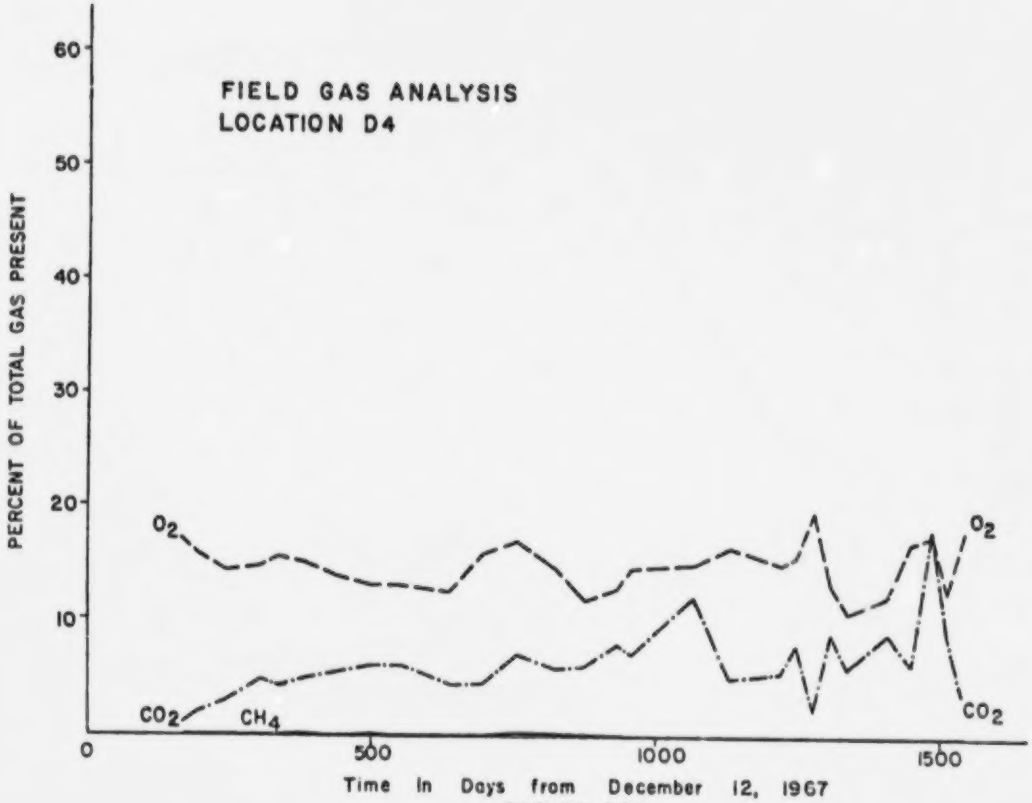

FIELD GAS ANALYSIS
LOCATION D4
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time In Days from December 12, 1967
O_2
CO_2
CH_4
O_2
CO_2

FIGURE 113

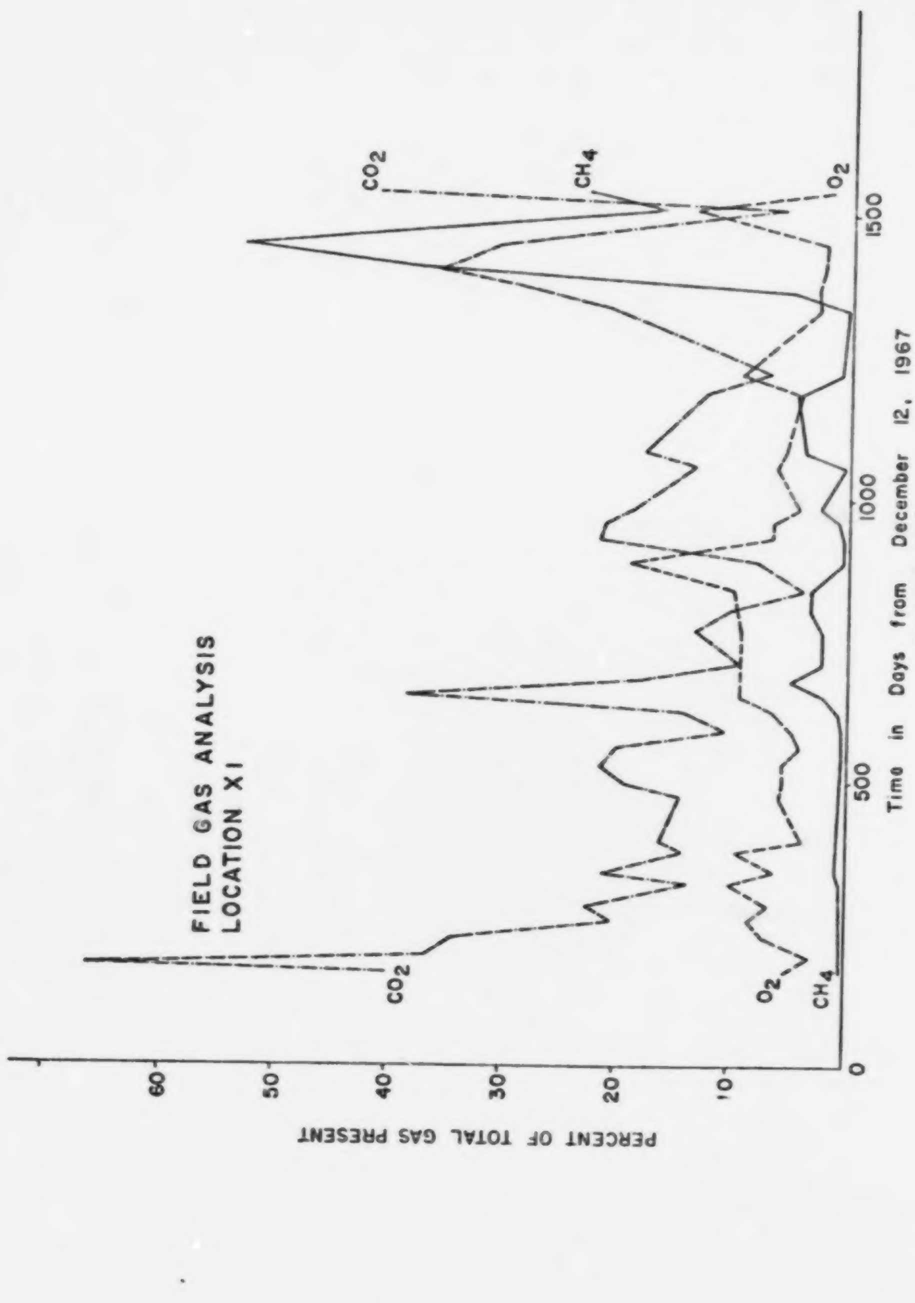

FIELD GAS ANALYSIS
LOCATION X1
PERCENT OF TOTAL GAS PRESENT
0
10
20
30
40
50
60
0
500
1000
1500
Time in Days from December 12, 1967
CO_2
O_2
CH_4
CO_2
CH_4
O_2

FIGURE 114

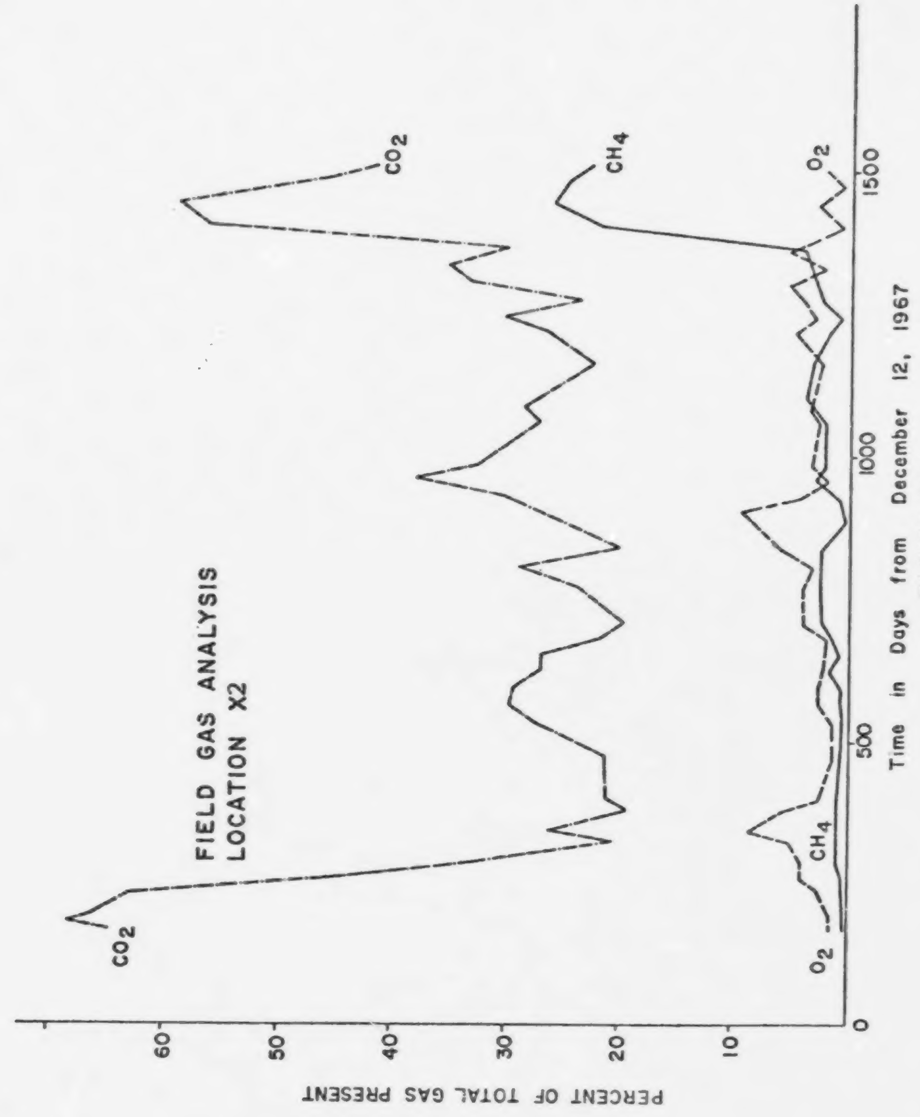

FIELD GAS ANALYSIS
LOCATION X2

FIGURE 115

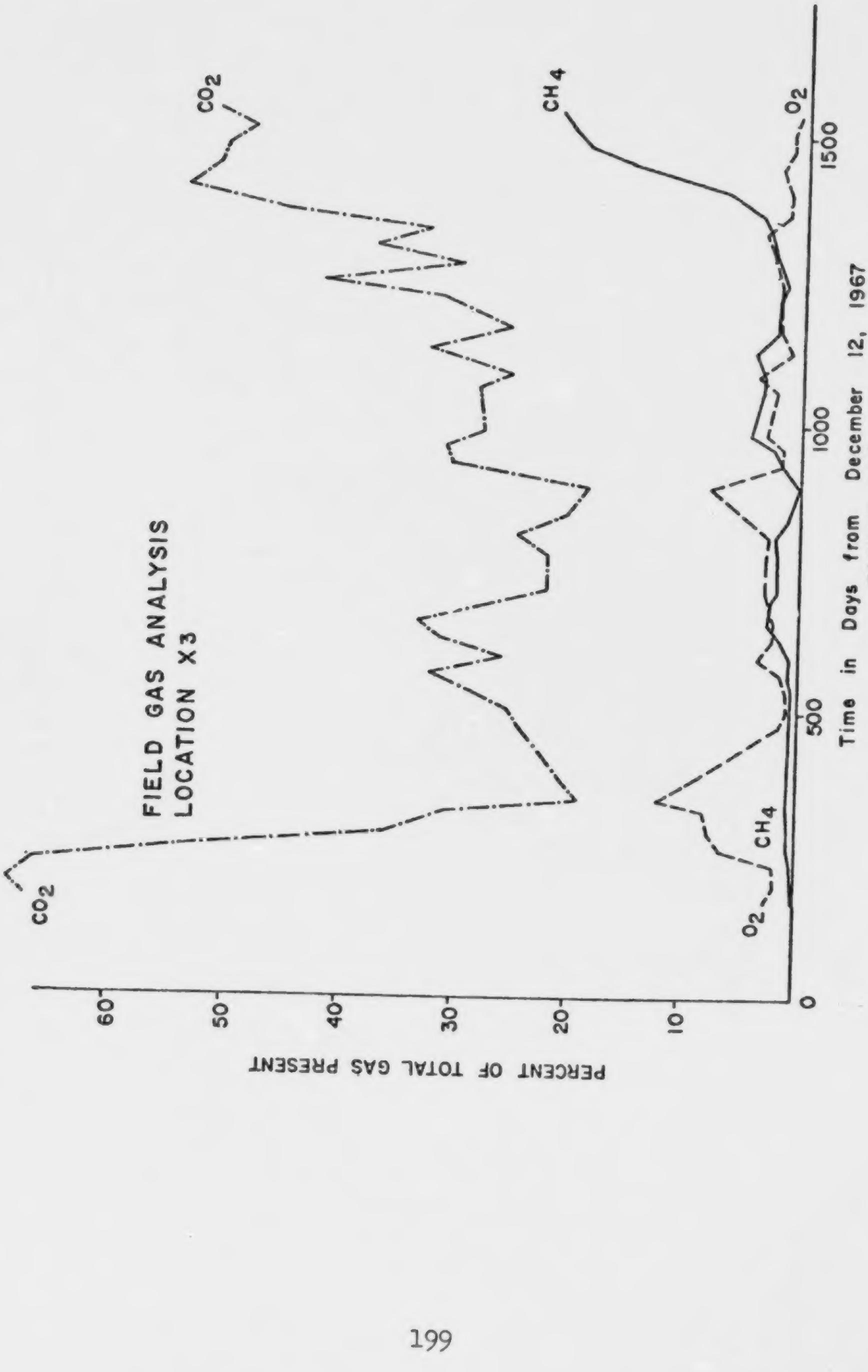

FIELD GAS ANALYSIS
LOCATION X3
PERCENT OF TOTAL GAS PRESENT
0
10
20
30
40
50
60
500
1000
1500
Time in Days from December 12, 1967
CO_2
CO_2
O_2
O_2
CH_4
CH_4

FIGURE 116

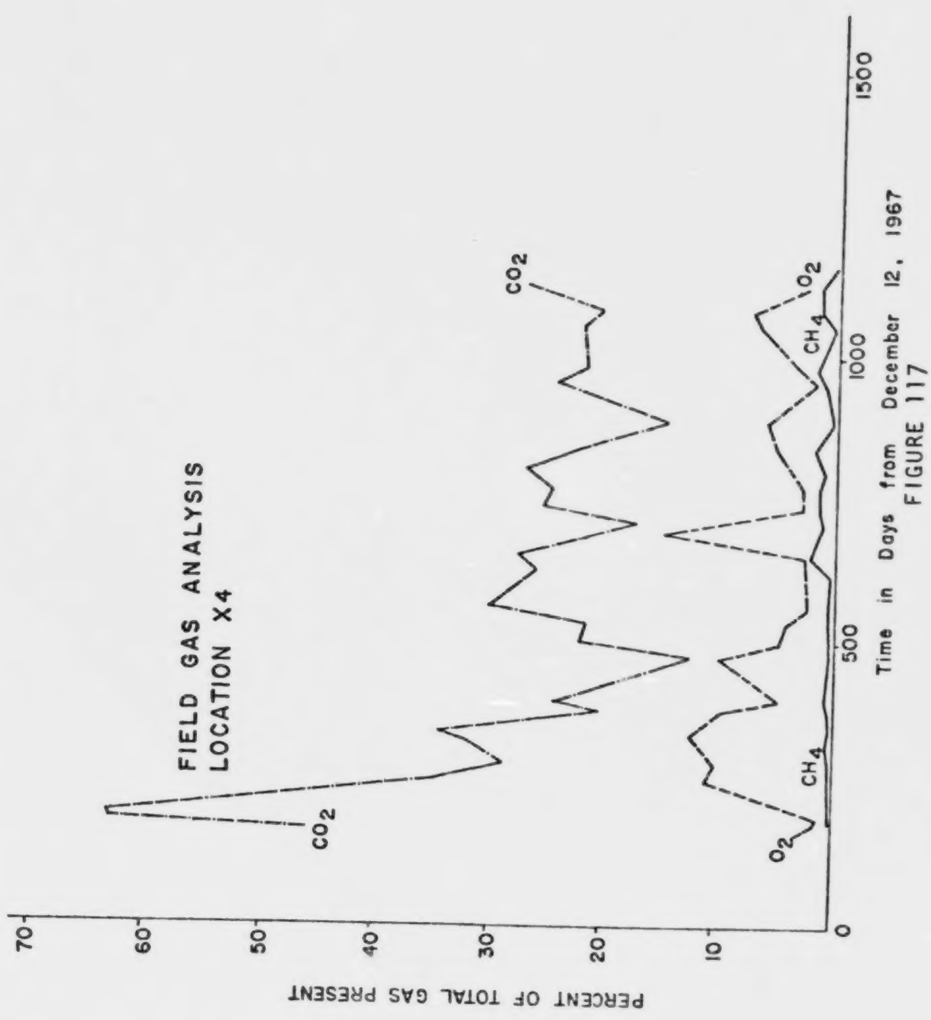

FIELD GAS ANALYSIS
LOCATION X4

FIGURE 117

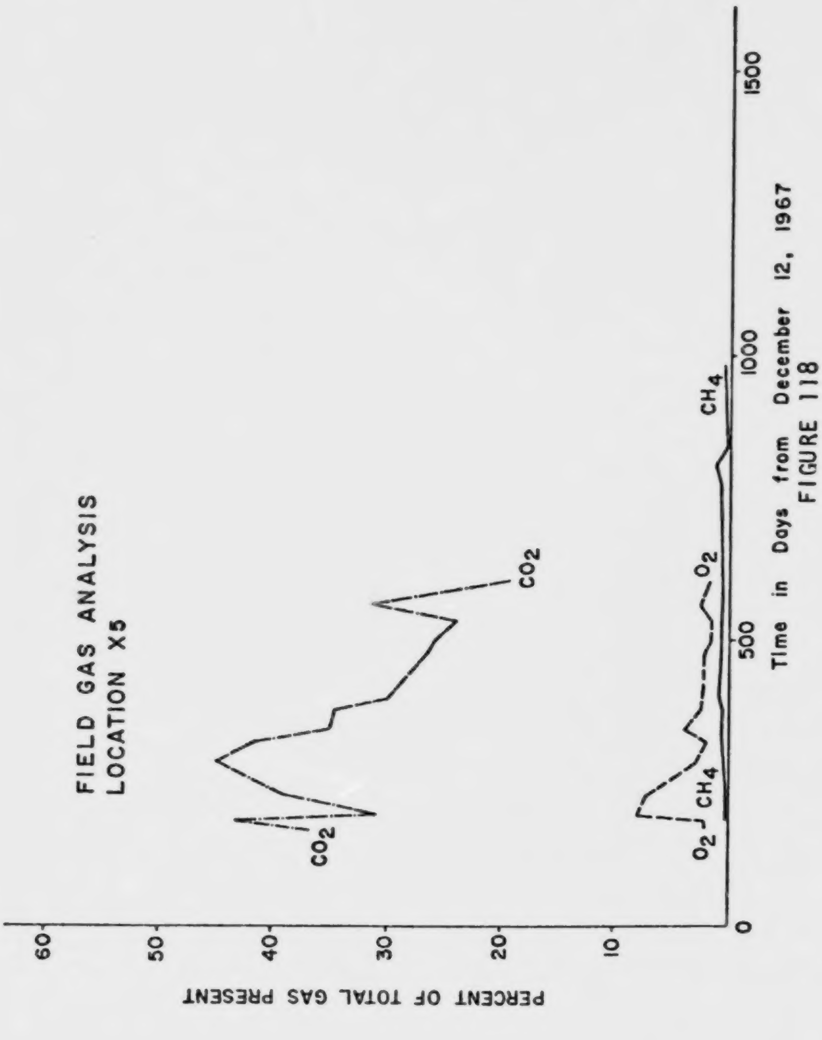

FIELD GAS ANALYSIS
LOCATION X5
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
CO_2
CO_2
O_2
CH_4
O_2
CH_4

FIGURE 118

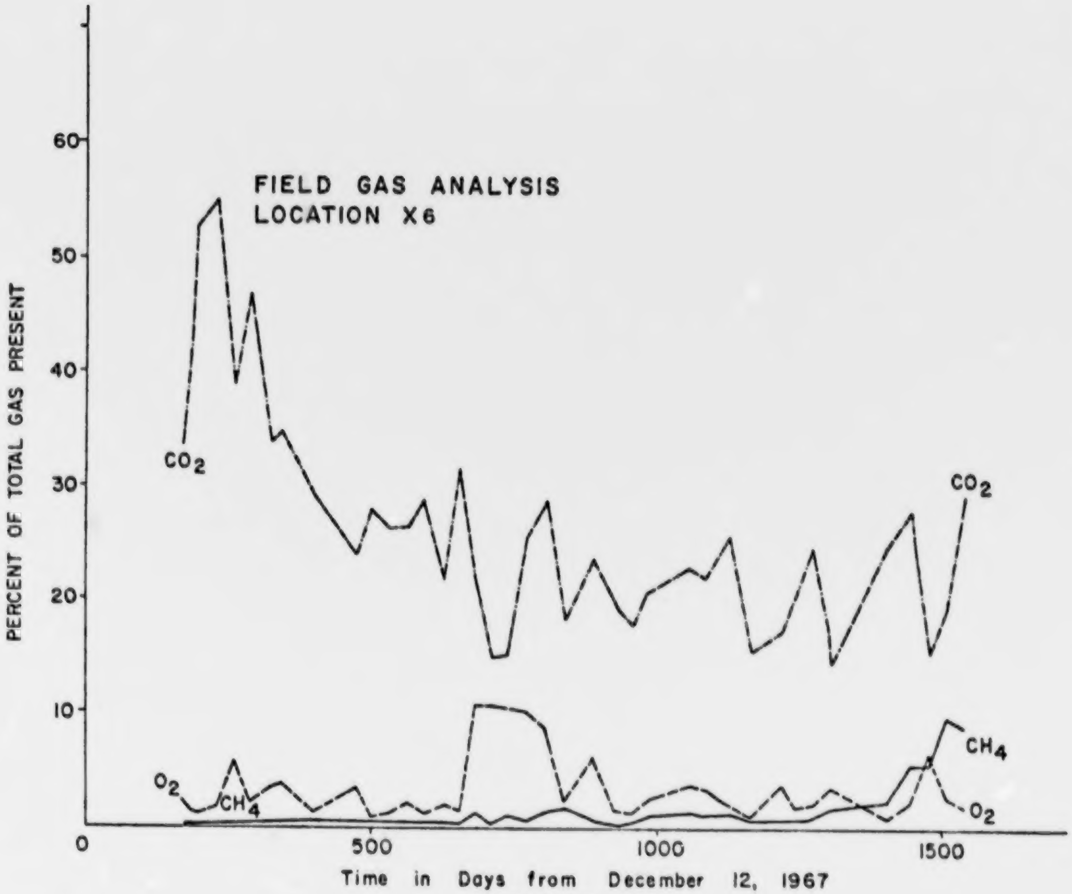

FIELD GAS ANALYSIS
LOCATION X6
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
CO_2
CO_2
O_2
CH_4
CH_4
O_2
Time in Days from December 12, 1967

FIGURE 119

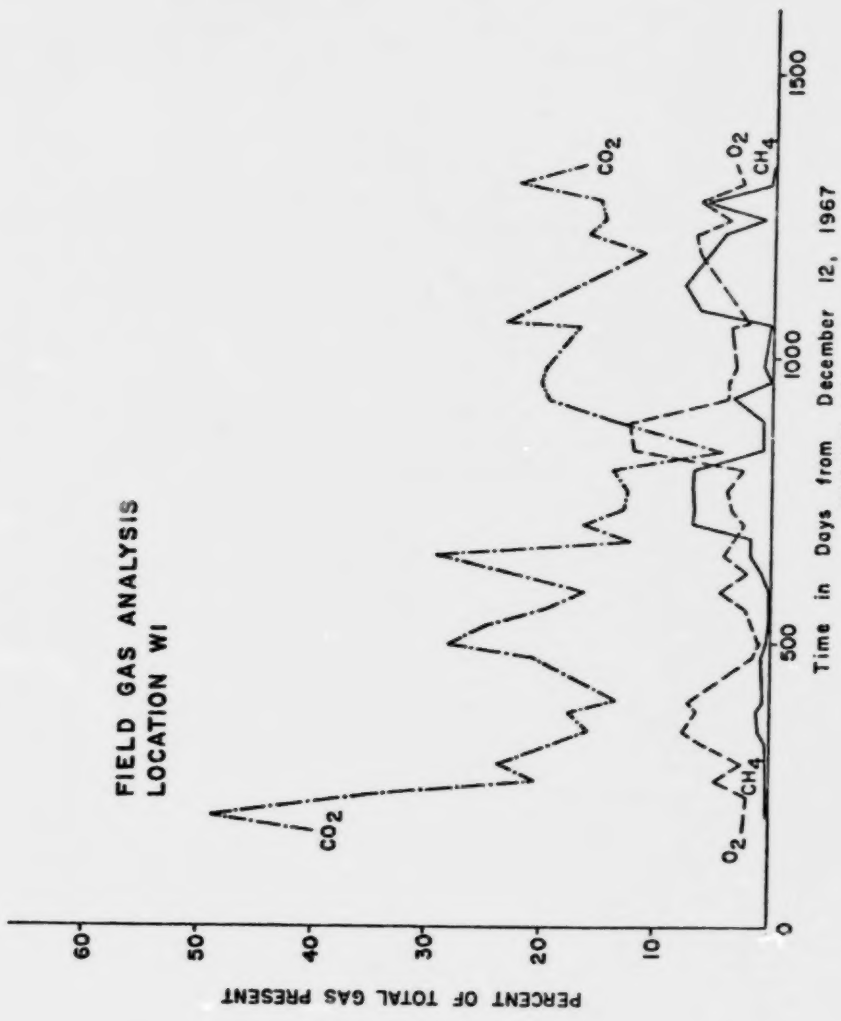

FIELD GAS ANALYSIS
LOCATION W1
PERCENT OF TOTAL GAS PRESENT
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
CO2
O2
CH4
CO2
O2
CH4

FIGURE 120

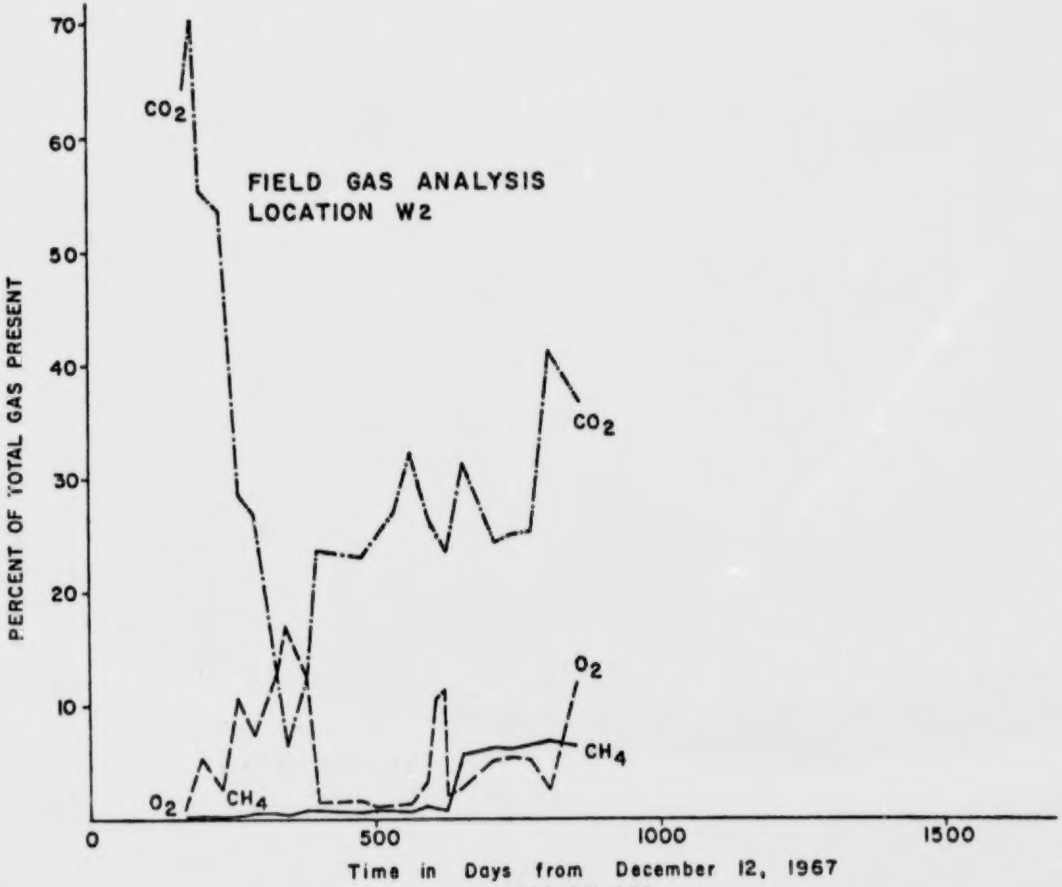

FIELD GAS ANALYSIS
LOCATION W2
PERCENT OF TOTAL GAS PRESENT
70
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
CO_2
CO_2
O_2
O_2
CH_4
CH_4

FIGURE 121

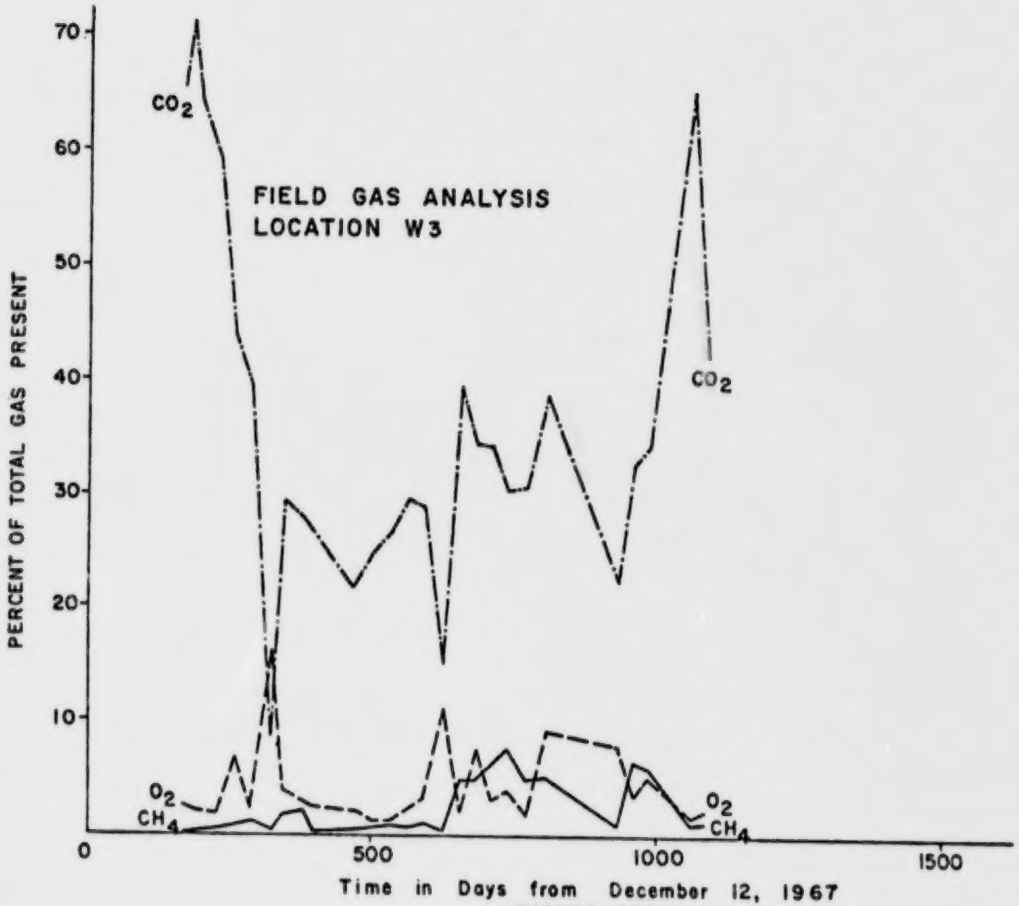

FIELD GAS ANALYSIS
LOCATION W3
PERCENT OF TOTAL GAS PRESENT
70
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
CO_2
CO_2
O_2
CH_4
O_2
CH_4

FIGURE 122

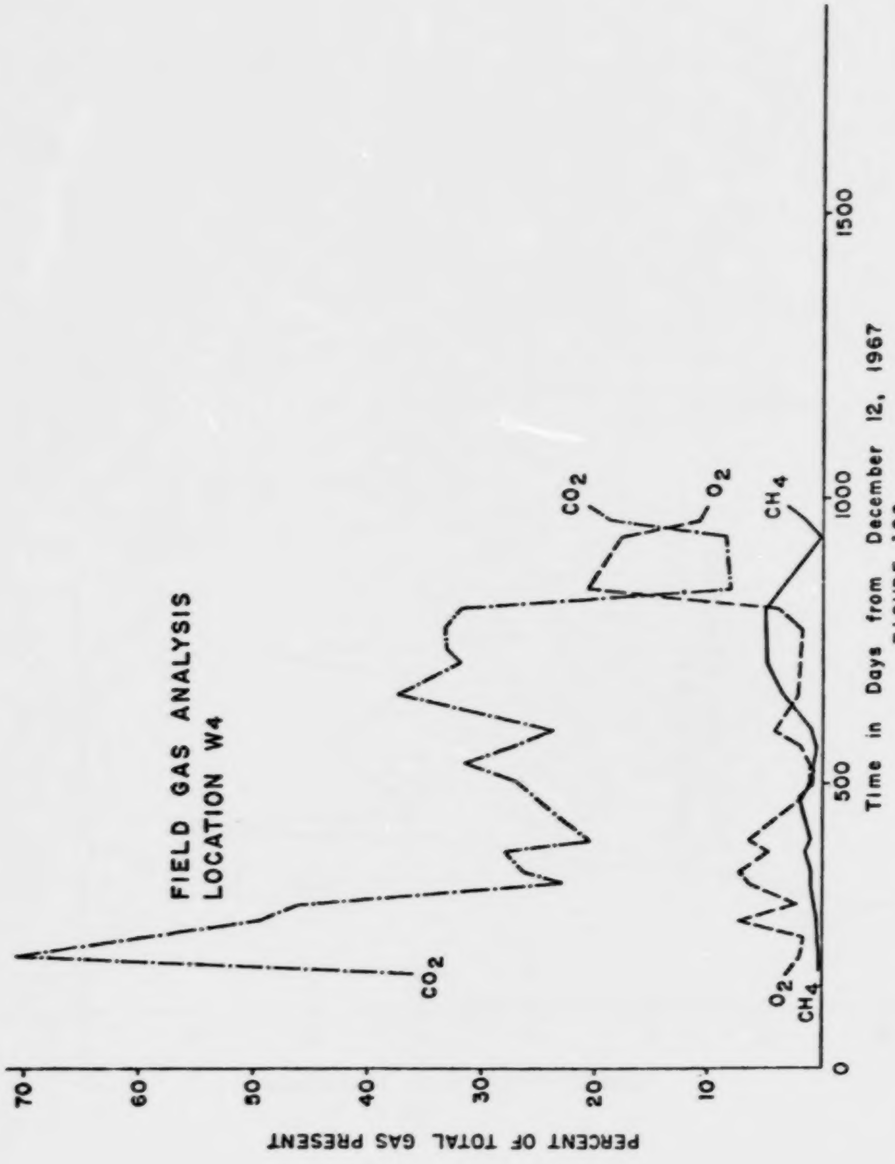

FIELD GAS ANALYSIS
LOCATION W4
PERCENT OF TOTAL GAS PRESENT
70
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
CO_2
O_2
CH_4
CO_2
O_2
CH_4

FIGURE 123

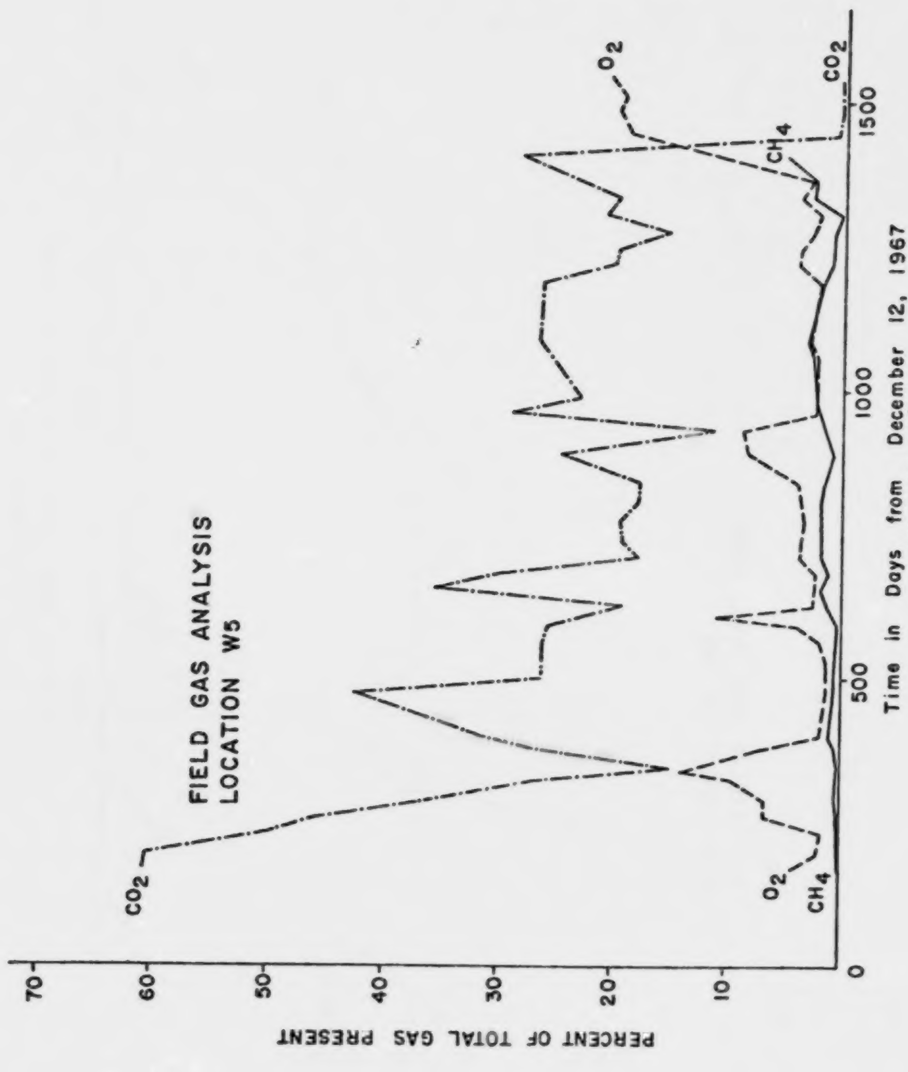

FIELD GAS ANALYSIS
LOCATION W5
PERCENT OF TOTAL GAS PRESENT
70
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
CO2
O2
CH4
CH4
O2
CO2

FIGURE 124

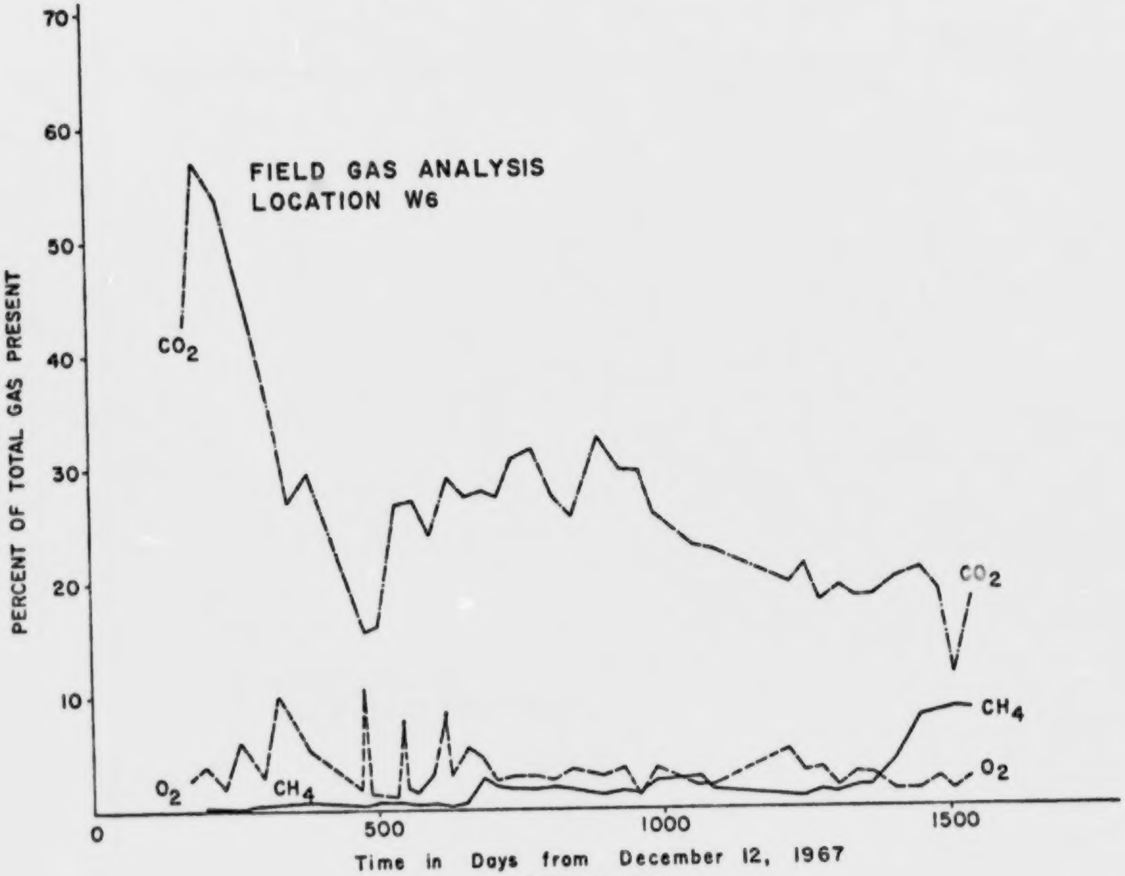

FIELD GAS ANALYSIS
LOCATION W6
PERCENT OF TOTAL GAS PRESENT
70
60
50
40
30
20
10
0
500
1000
1500
Time in Days from December 12, 1967
CO_2
CO_2
O_2
CH_4
CH_4
O_2

FIGURE 125

the "A" series, "D" series and "X" series, inside the test cell, indicates that while methane generation occurs within the cell, little escapes into the surrounding soil.

These results reflect primarily on the relative pervious nature of the residual soils* and the ability of the gas to vent through the soil cover to the atmosphere. These results are not presented to suggest either a lack of gas migration into the surrounding soil or the universal application of the results to other soil-landfill systems. However, the results do suggest the need to carefully assess each case on an individual basis and not to pre-suppose the existence of a gas problem.

The "X" series and "W" series of gas data curves, Figures 114 through 125, are representative of gas generation patterns within the test cell. Unfortunately in some of the other quadrants, the gas tubes clogged and samples were collected for only short periods of time.

Carbon dioxide concentrations are initially high and remain relatively high for the entire test period. In the "W" series methane concentrations never developed significant continuous trends. Further, the methane concentrations remain relatively low.

The "X" series results indicate consistently higher methane concentrations. However, the most active period began after approximately thirteen hundred days into the test. It is interesting to note that the most active layers were in the center of the test cell with little methane buildup at the top or bottom. This suggests free migration of methane from below the landfill as well as free movement of air into the bottom of the landfill. This combined gas migration pattern would tend to reduce methane gas concentrations, thereby reducing the possibility of vertical or lateral movement. This pattern differs significantly from the pattern for the lysimeter where the lower boundary was impervious. In this case, gas concentrations tend to increase to maximum values with depth.

Methane concentration reached peaks of thirty (30) to forty (40) percent after fifteen hundred days. The net result is the development of potentially explosive situation if the gas so generated migrated into a closed environment. This behavior pattern clearly indicates that ambient temperature conditions, the rate of moisture buildup to field capacity and initial refuse density can have a marked effect on the rate of degradation, hence the rate of methane buildup.

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*See Soils & Geology Section.

Gas measurements are important enough to be an integral part of any landfill operation. However, as the study results suggest, a careful evaluation of the gas monitoring system is essential to insure optimum stabilization of any proposed gas purging scheme.

Field Leachate

Several monitoring systems for leachate migration detection and sampling were installed both within the refuse and the subsurface soils down to and below the ground water table.

The monitoring systems consisted of suction lysimeters, deep wells and shallow well clusters. The suction lysimeters (designated as "U" series) were installed at depths of one (.305 m.), four (1.22 m.), six (1.83 m.), eight (2.44 m.), eleven (3.35 m.), thirteen (3.96 m.), and eighteen (5.49 m.) feet below the ground surface. U1, U4, U6 and U8 were in the refuse. U11, U13, U18 were below the refuse.

The deep wells were installed simply to sample ground water between the depths of twenty (20) (6.1 m.) and thirty-five (35) (10.67 m.) feet. These wells were installed prior to placement of the refuse except for two below the refuse. The latter two wells were installed after the refuse was placed. These wells carry the designation 1 through 14. Wells 1 through 11 were used to obtain the background water quality data reported earlier in this section.

The shallow wells were installed in clusters adjacent to the deep wells. The wells in clusters of three were used to monitor ground water at depth increments of 21 (6.4) to 23 feet (7.01 m.), 23 (7.01) to 25 feet (7.62 m.), and 25 (7.62) to 28 feet (8.53 m.). On occasion, the 21 (6.4) to 23 feet (7.01 m.) well would be dry as the ground water table dropped. These wells are designated by a double letter notation with a number designating its maximum depth of monitoring (i.e. - SF28 is in the SF cluster and monitors between 25 (7.62 m.) and 28 feet (8.53 m.).

Water Feeding Program

The field test cell was subjected to the natural precipitation and evapotranspiration regimen of the southeastern Pennsylvania region. To encourage infiltration the top of the test cell was contoured to retain as much water as possible and the vegetation was kept to a minimum. As noted elsewhere, the field cell was placed into operation in May, 1968. Between May 1968 and October 1969, there was insufficient precipitation to bring the cell to field capacity.

In October, 1969, the equivalent of 5.10 inches (129.54 mm.) of water infiltration was added to the surface of the cell to bring it to field capacity, and thereafter the natural precipitation-evapotranspiration regimen was again followed. Substantially increased quantities of leachate were obtained after the test cell was brought to field capacity. The curves for the various leachate monitoring systems reflect the delay in leachate production by their being offset from the time zero date of May 10, 1968.

Field Suction Lysimeter Leachate

The curves in Figures 126 through 130 are for the suction lysimeters U-6, U-8, U-11, U-13 and U-18. Suction lysimeters U-1 and U-4 in the upper portion of the refuse never produced leachate of a substantial quantity and are believed to have become clogged early in the study.

The results in the Figures are for total dissolved solids. Complete results can be found in the data volume. Total dissolved solids curves have been selected as typical of all the contaminants evaluated in this study.

Of particular interest in these curves is the significant first peak which occurs at approximately 800 days into the study. This time corresponds to the addition of the large quantity of water to bring the test cell to field capacity. Within the test cell, U-6 and U-8, a rapid buildup in TDS to approximately 6000 mg/l occurs. A corresponding increase in TDS occurs at the same time in the leachate from lysimeters U-11 and U-13.

After that initial release, leachate from U-6 and U-8 shows relatively high TDS with another peak to approximately 9000 mg/l.

The leachate from the suction lysimeters below the test cell do not show the TDS increase and, in fact, do not exceed 3,000 mg/l during the remainder of the test period. (Note that suction lysimeter U-18 failed to function past 800 days into the test).

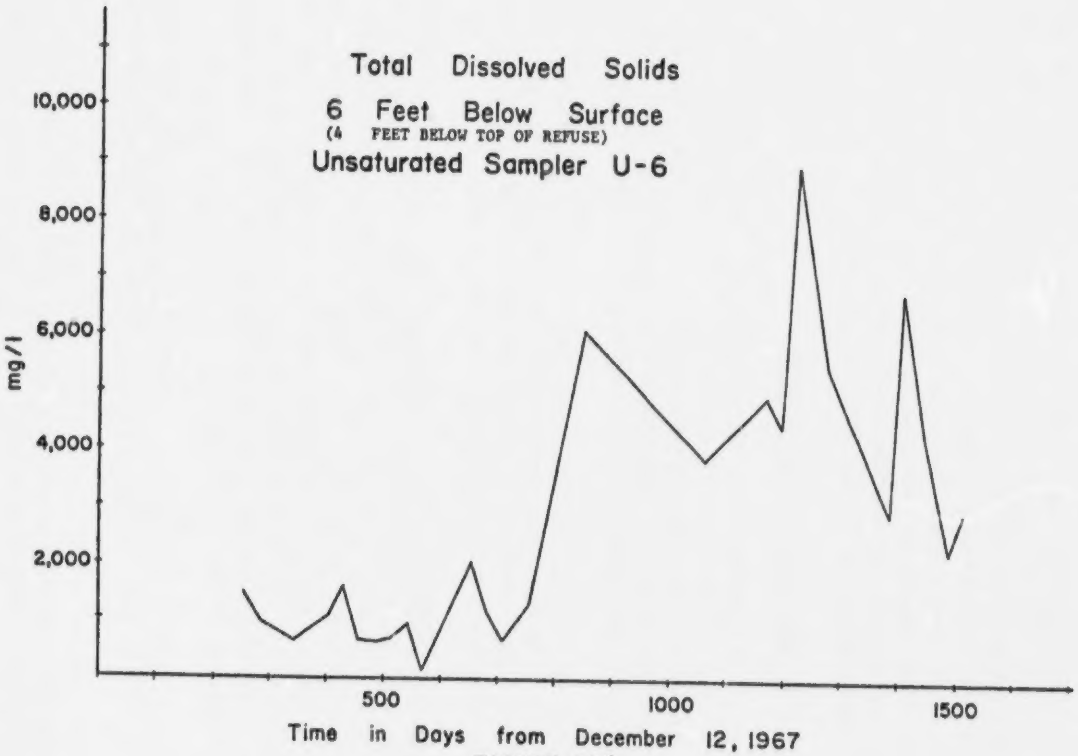

Total Dissolved Solids
6 Feet Below Surface
(4 FEET BELOW TOP OF REFUSE)
Unsaturated Sampler U-6
10,000
8,000
6,000
4,000
2,000
mg/l
500
1000
1500
Time in Days from December 12, 1967

FIGURE 126

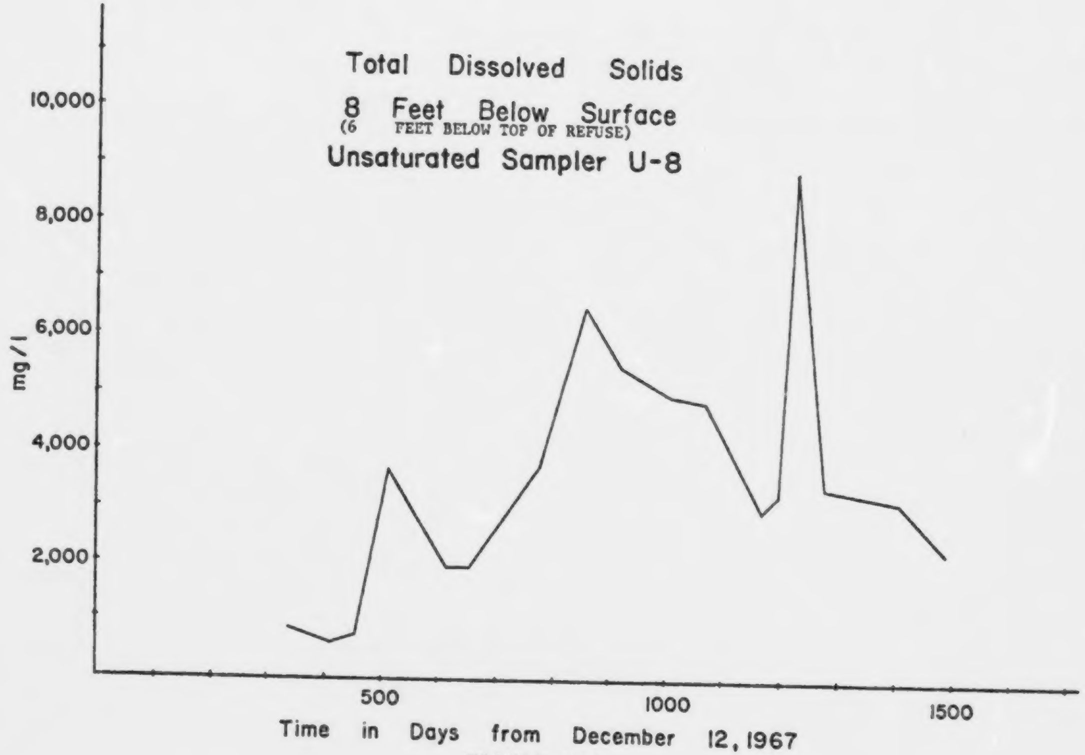
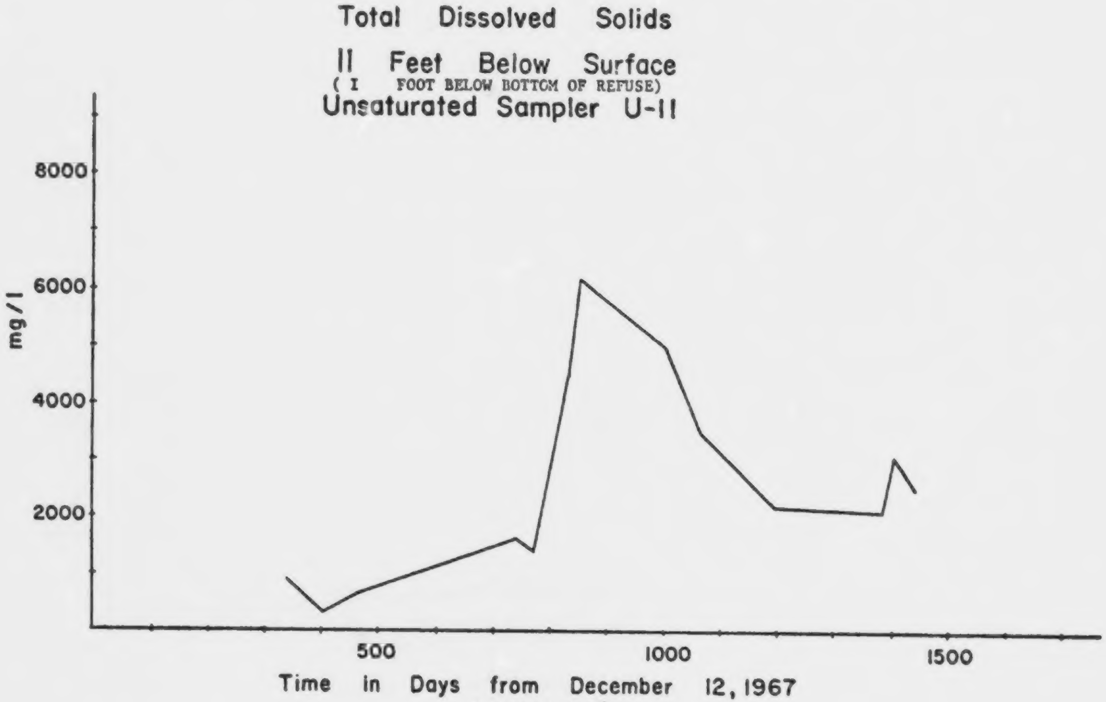

Total Dissolved Solids
8 Feet Below Surface
(6 FEET BELOW TOP OF REFUSE)
Unsaturated Sampler U-8

FIGURE 127



Total Dissolved Solids
11 Feet Below Surface
(I FOOT BELOW BOTTOM OF REFUSE)
Unsaturated Sampler U-11

FIGURE 128

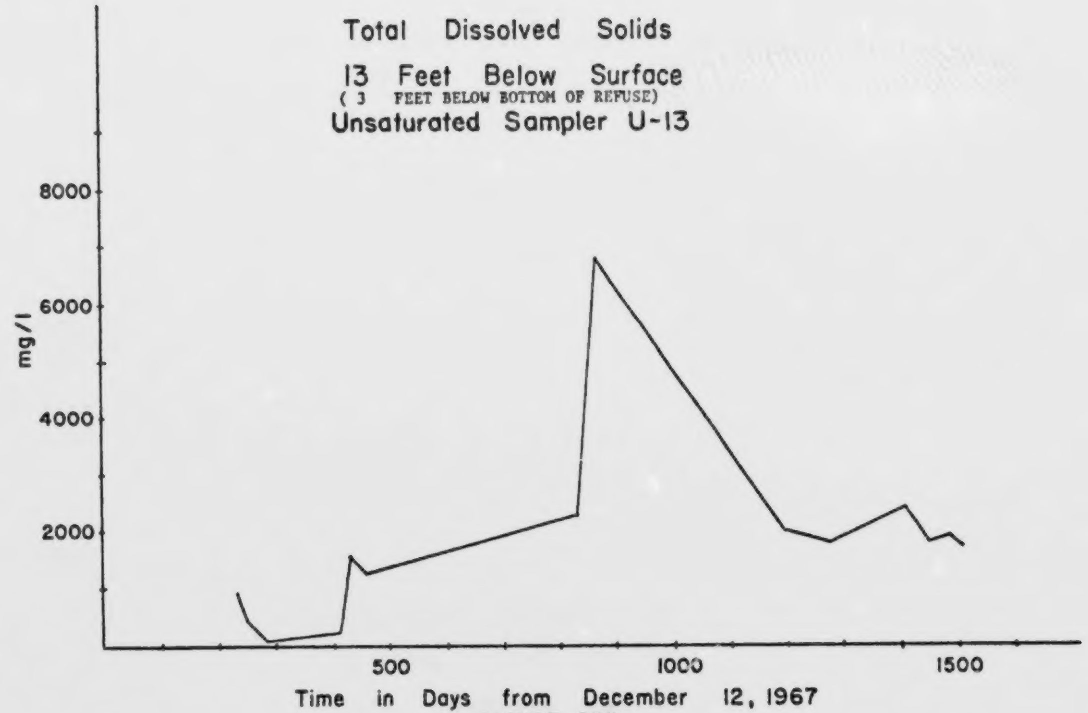
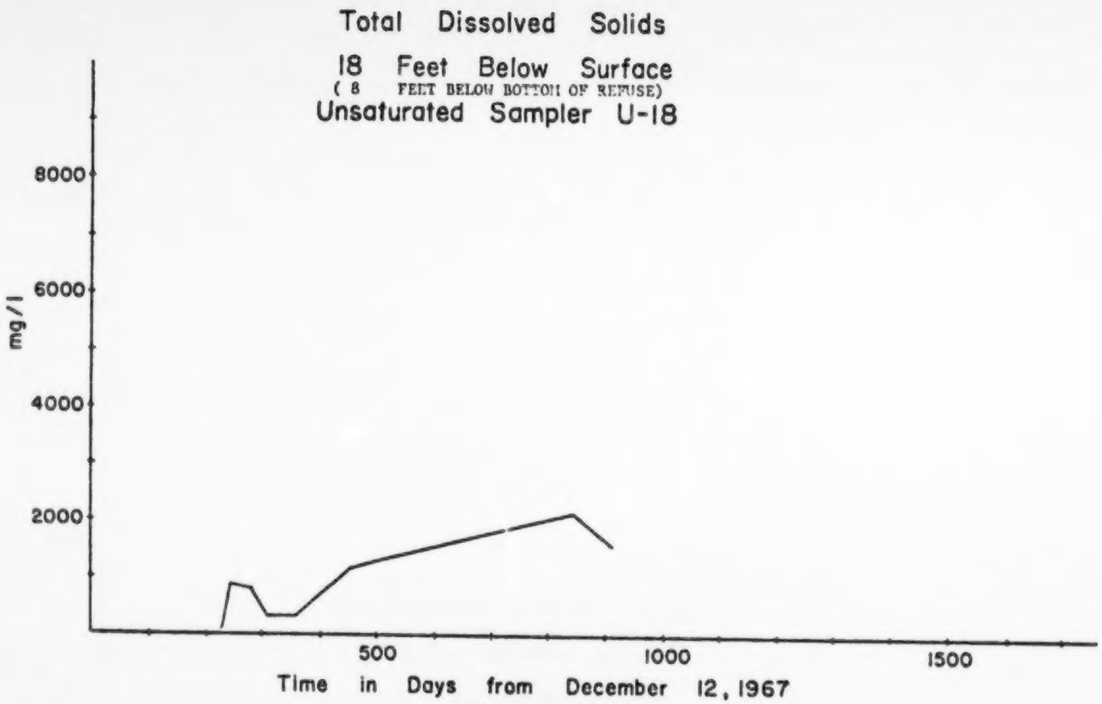

Total Dissolved Solids
13 Feet Below Surface
(3 FEET BELOW BOTTOM OF REFUSE)
Unsaturated Sampler U-13
mg/l
8000
6000
4000
2000
500
1000
1500
Time in Days from December 12, 1967

FIGURE 129



Total Dissolved Solids
18 Feet Below Surface
(8 FEET BELOW BOTTOM OF REFUSE)
Unsaturated Sampler U-18

FIGURE 130

The results indicate that for moderate quantities of water, the soil has the capacity to reduce TDS concentrations (and most of the other contaminants) as long as the loading rate is not excessive. Hence, a properly designed site with a suitable soil buffer zone requires control of the infiltration to permit proper soil renovation of the leachate.

Field Deep Well Study

The data from wells number 12 and 13 beneath the refuse(Figs. 131-143) and well number 3 are presented as typical of the deep ground water wells. The general direction of ground water is from the northeast to the southwest. Therefore, the data from well number 3 represents the influence of leachate migration on ground water quality(Figs. 144-149).

Wells 12 and 13 -

pH - Tends to be slightly acidic at about 6.0. Occasionally, decreases to 5.0 and increases to 7.5 to 8.0. Overall pH falls between 5.0 and 8.0 with a mean about 6.0.

COD - Except for a rapid rise to approximately 2700 at 800 days into the test, COD remains very low. COD results are substantially lower than obtained in the laboratory tests. Again, it is noteworthy that a rapid rose occurred during the period of flooding to bring the refuse to field capacity.

Iron - Iron in well 12 rises after 800 days to a peak of 225 mg/l. For the remainder of the test it never exceeds 125 mg/l. Iron in well 13 rises to 700 mg/l 400 days into the test and thereafter does not exceed 100 mg/l.

While these results are incompatible, it is believed they reflect refuse placement as well as ground water flow influences.

TDS - The results in TDS in wells number 12 and 13 show that significant increases in TDS concentrations occur approximately 1300 days into the test. Thereafter they remain high but vary rapidly and substantially from test to test. Even though concentrations increase greatly, they do not reach the magnitude obtained in the suction lysimeters. These results are due to both the soil renovation capacity and ground water dilution.

The composite TDS figure for wells 12 and 13 extend the results to 1500 days. It is noteworthy that a rapid rise in TDS occurs in well 13 during this latter time period.

pH
TEST WELL No.12

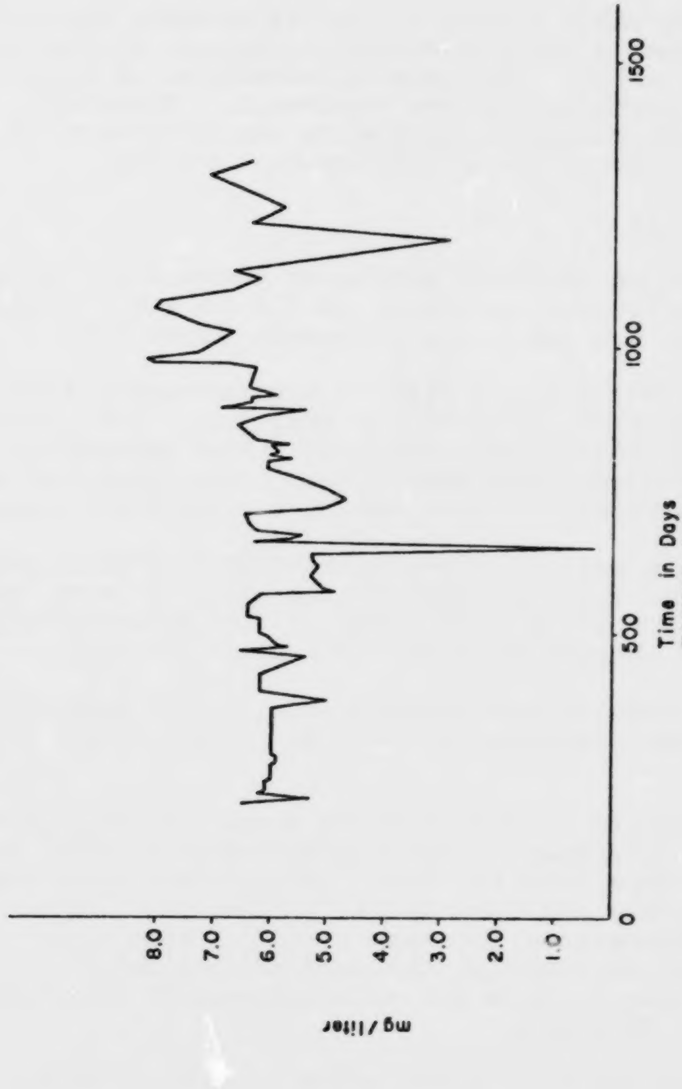


FIGURE 131

CHEMICAL OXYGEN DEMAND
TEST WELL No. 12

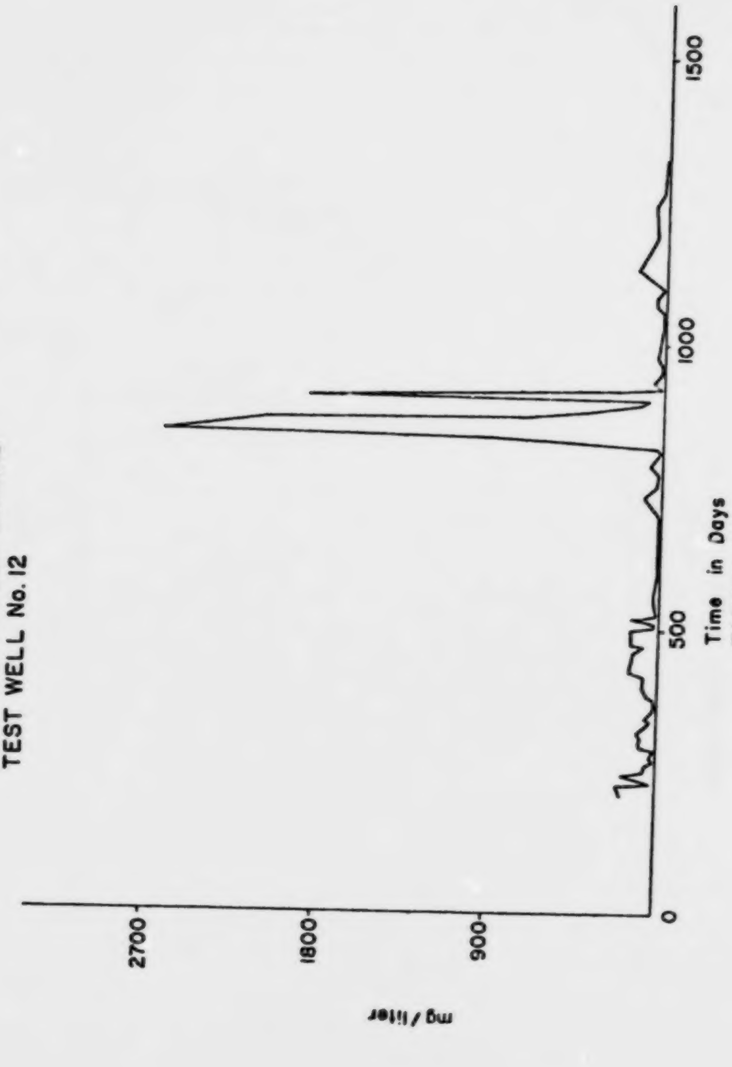


FIGURE 132

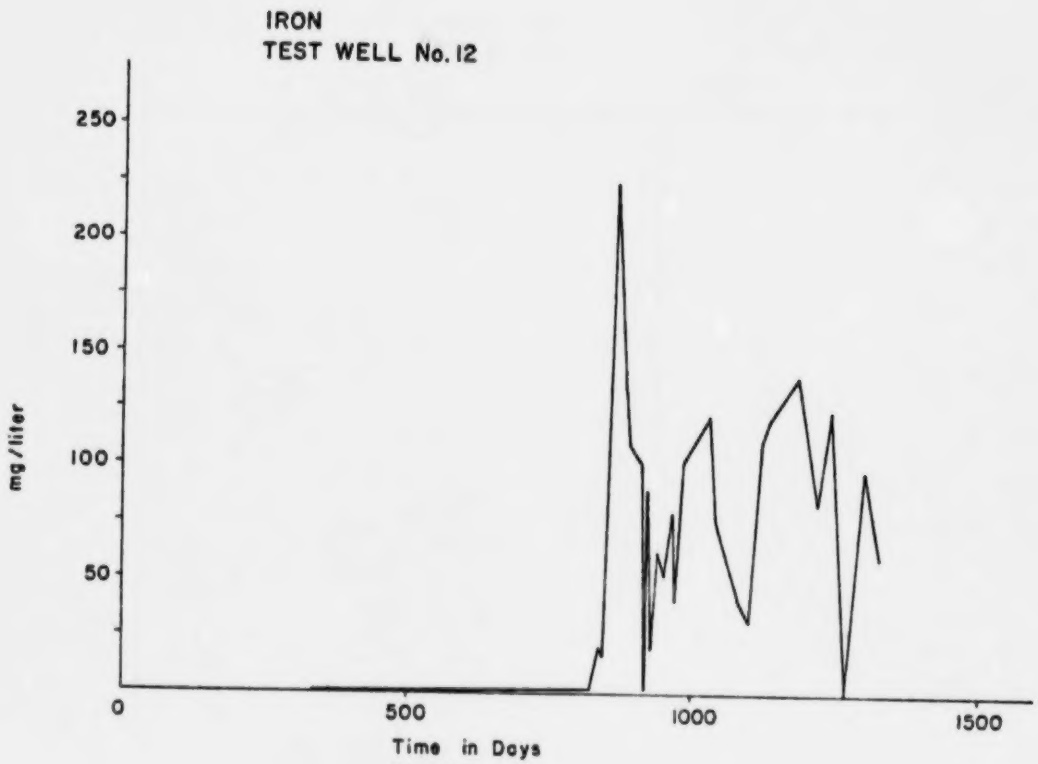

IRON
TEST WELL No. 12
250
200
150
100
50
mg/liter
0
500
1000
1500
Time in Days

FIGURE 133

TOTAL DISSOLVED SOLIDS
TEST WELL No. 12

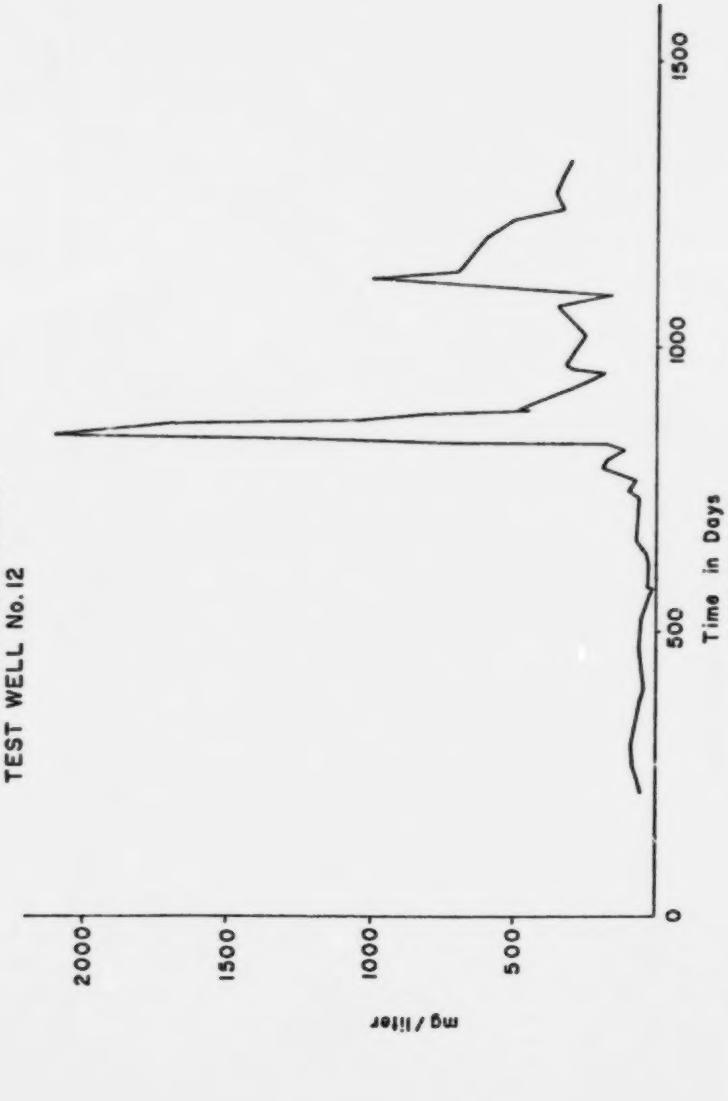


FIGURE 134

CHLORIDE
TEST WELL No.12

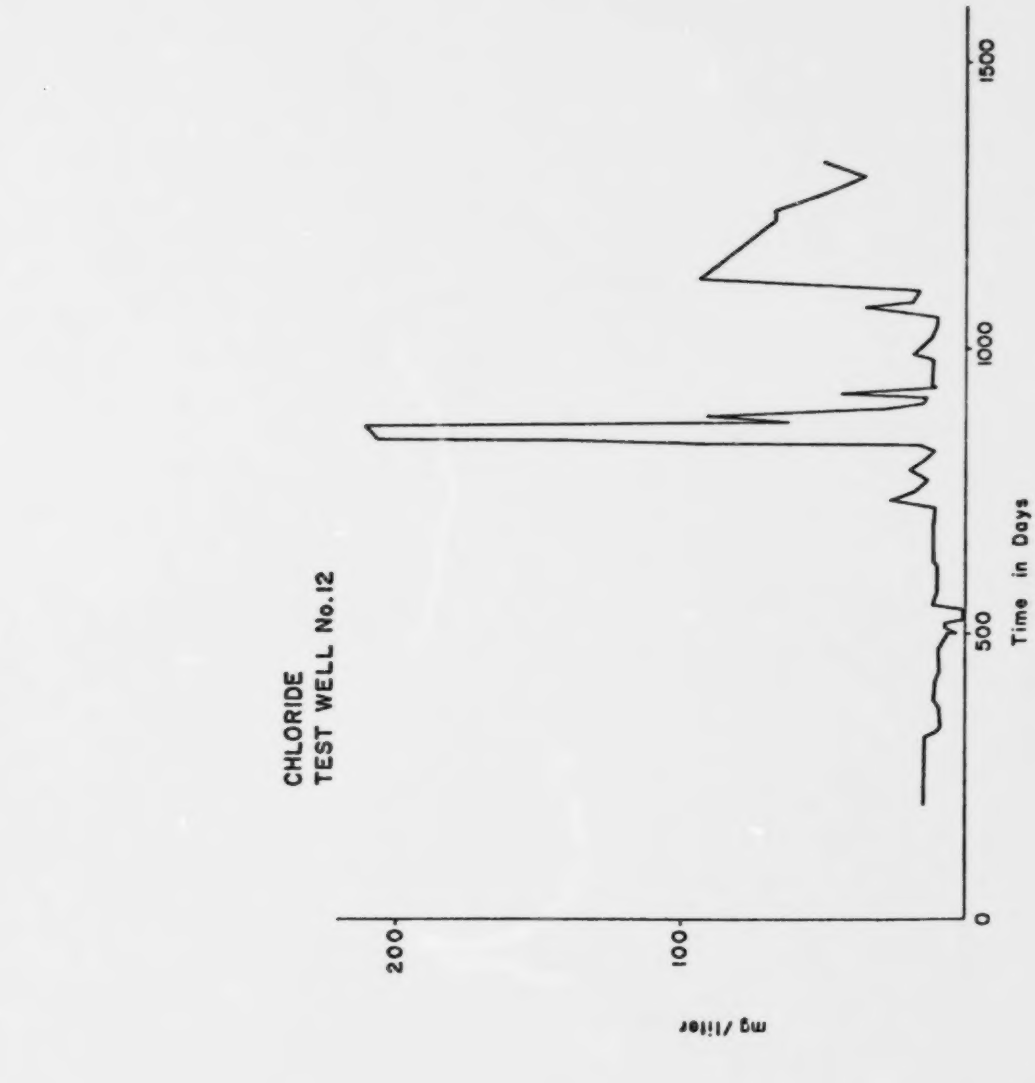


FIGURE 135

SODIUM
TEST WELL No. 12

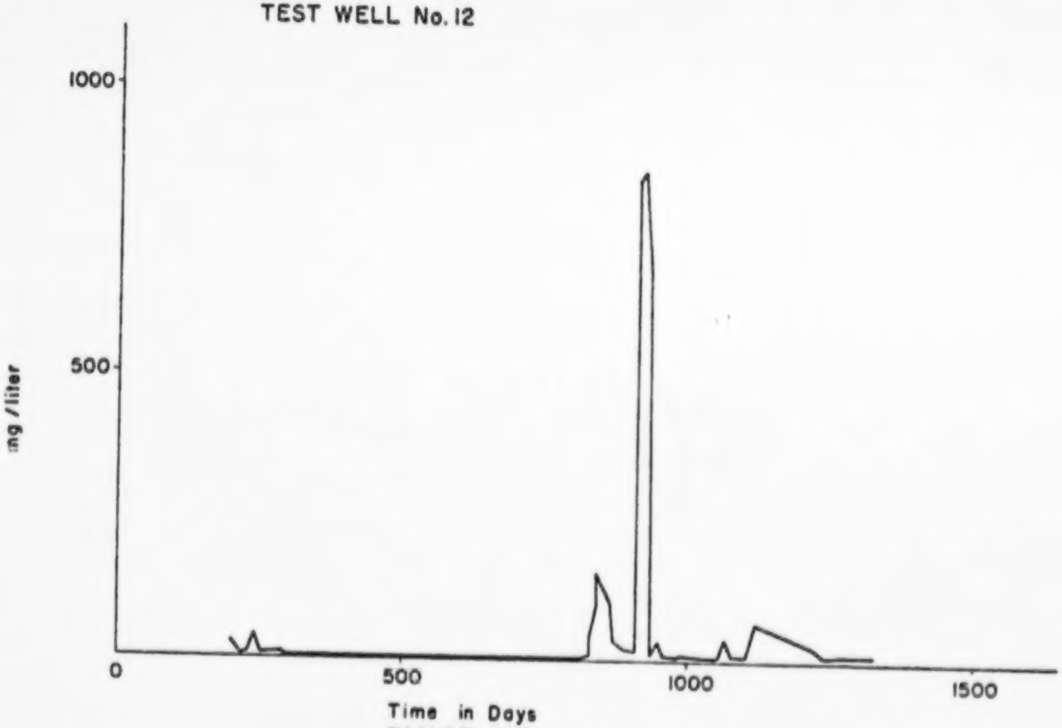


FIGURE 136

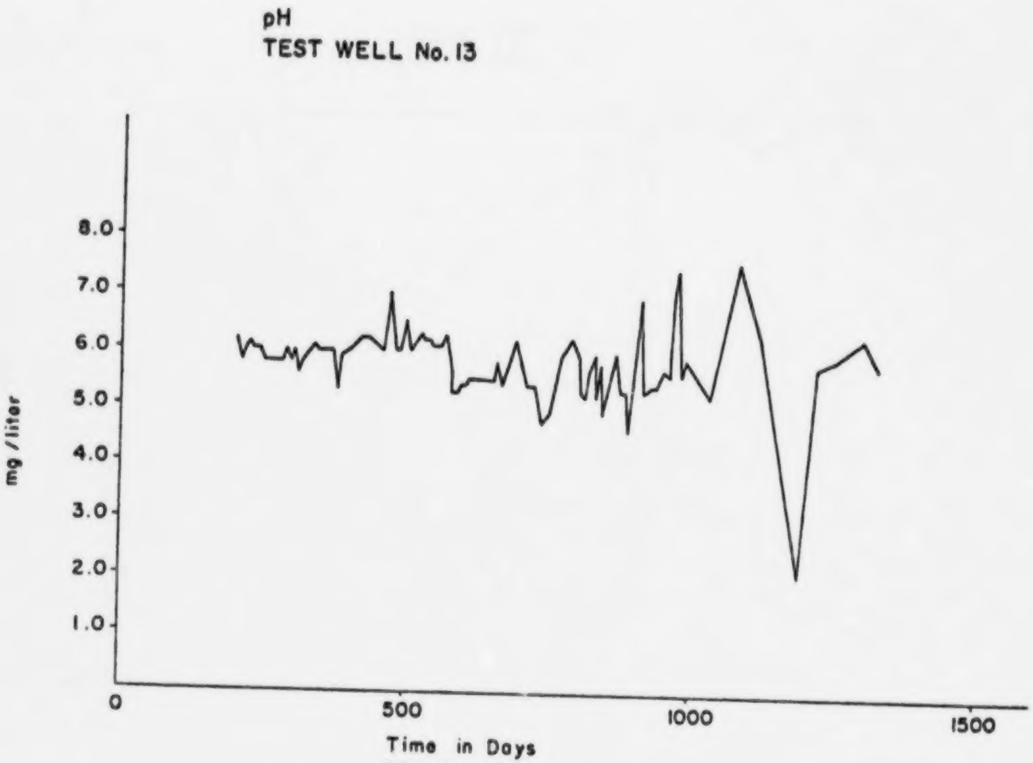

pH
TEST WELL No. 13

FIGURE 137

CHEMICAL OXYGEN DEMAND
TEST WELL No. 13

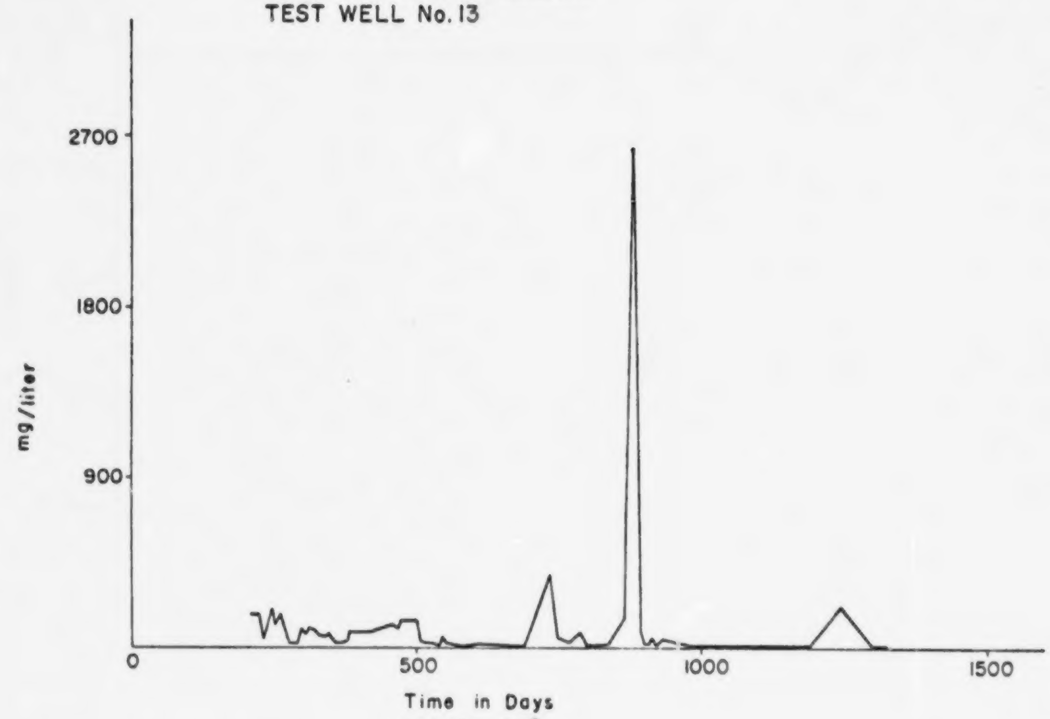


FIGURE 138

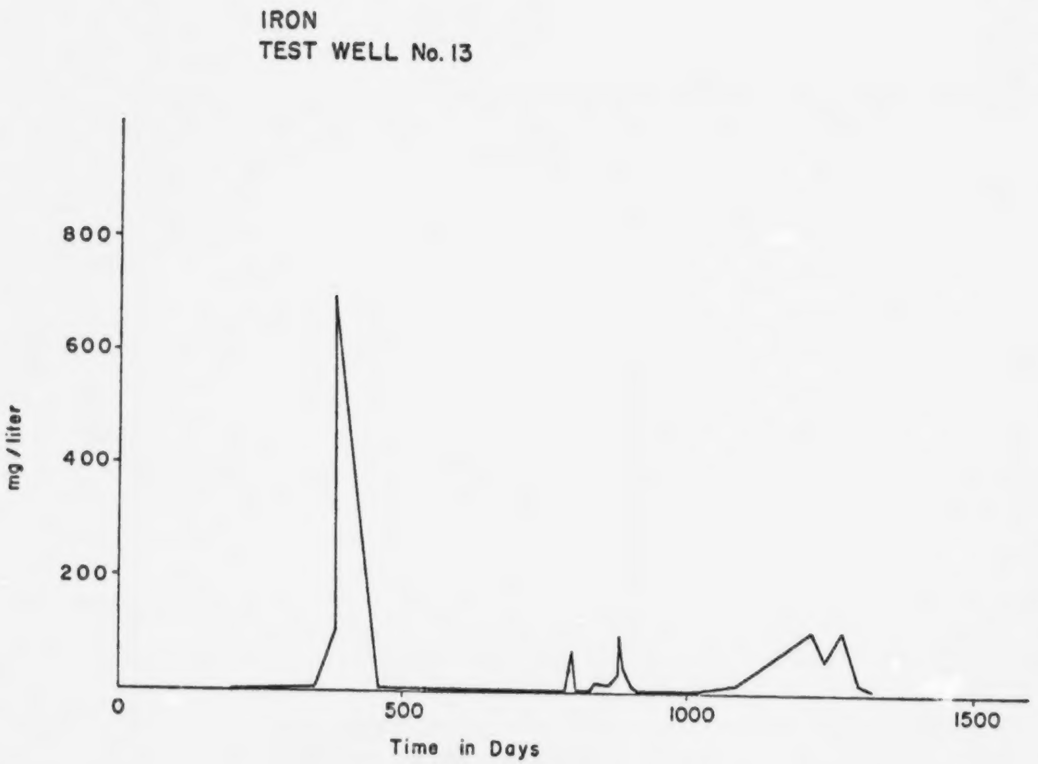
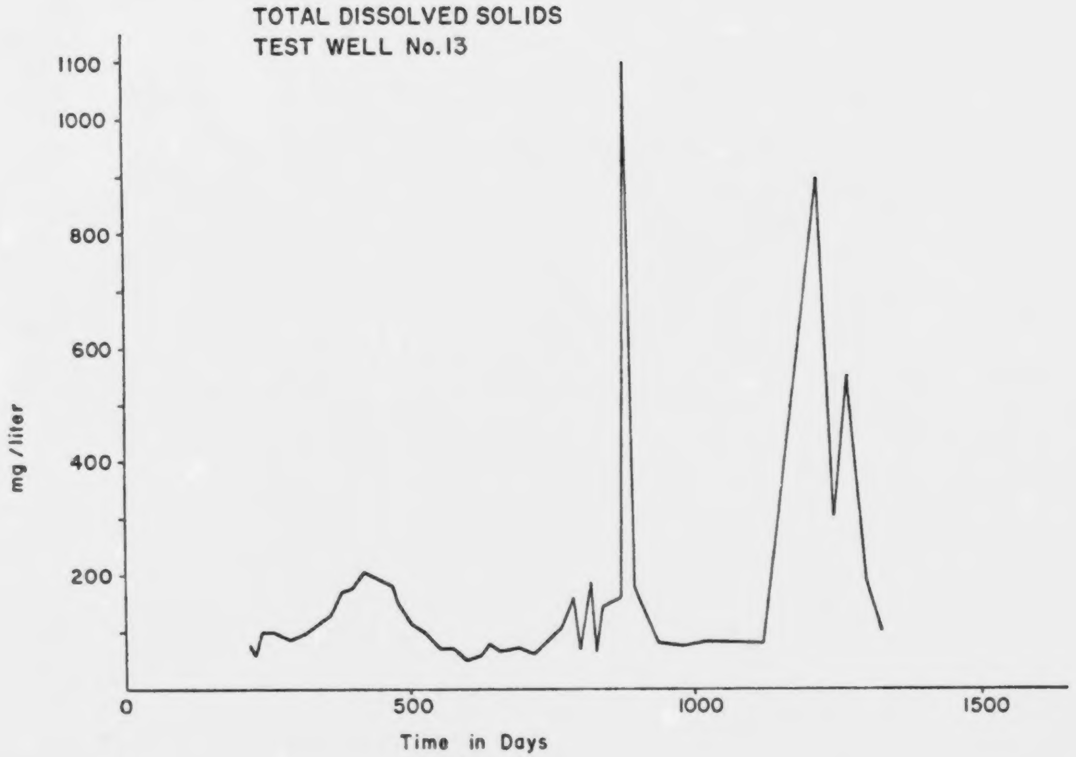

IRON
TEST WELL No. 13
800
600
400
200
mg / liter
0
500
1000
1500
Time in Days

FIGURE 139



TOTAL DISSOLVED SOLIDS
TEST WELL No.13

FIGURE 140

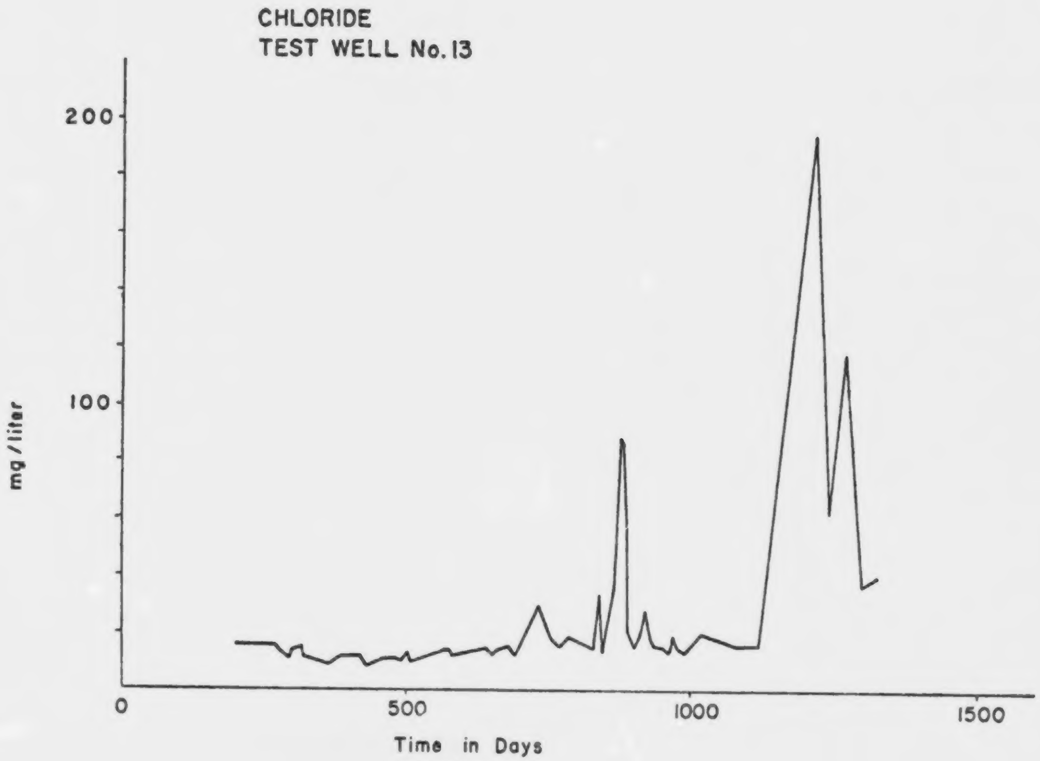

CHLORIDE
TEST WELL No. 13
200
100
mg / liter
0
500
1000
1500
Time in Days

FIGURE 141

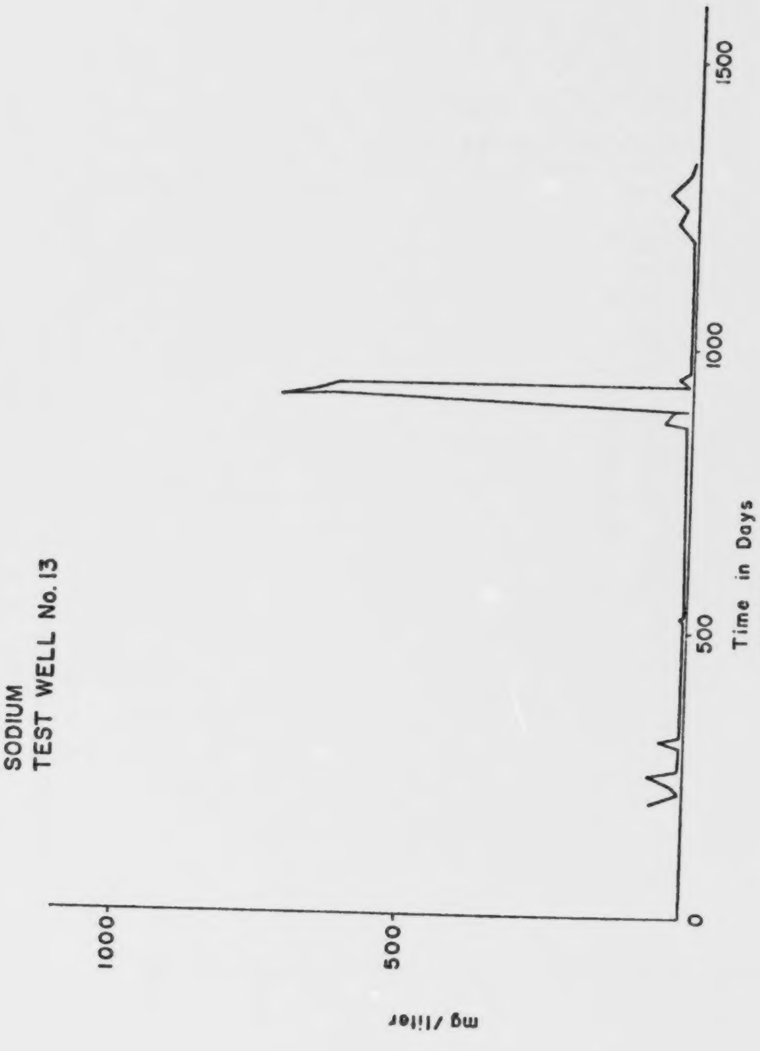

SODIUM
TEST WELL No. 13
mg / liter
1000
500
0
500
1000
1500
Time in Days

FIGURE 142

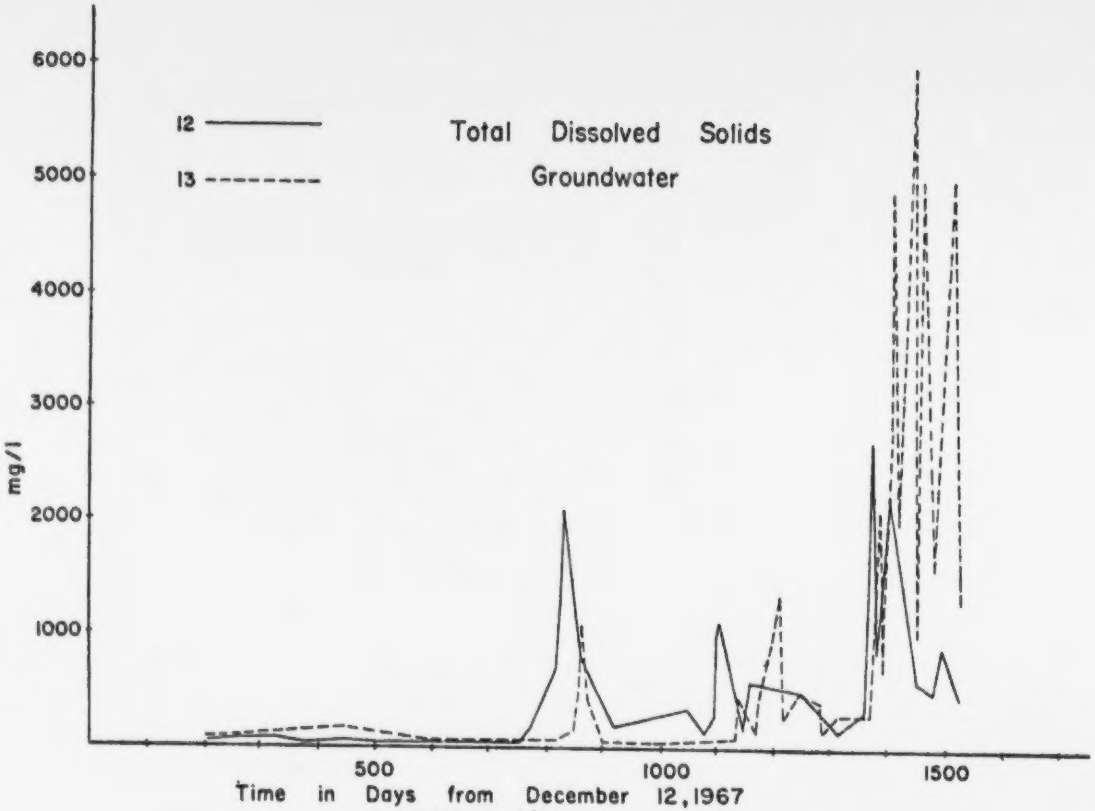

6000
5000
4000
3000
2000
1000
mg/l
12 ———
13 - - - - - - - -
Total Dissolved Solids
Groundwater
500
1000
1500
Time in Days from December 12, 1967

FIGURE 143

pH
TEST WELL No.3

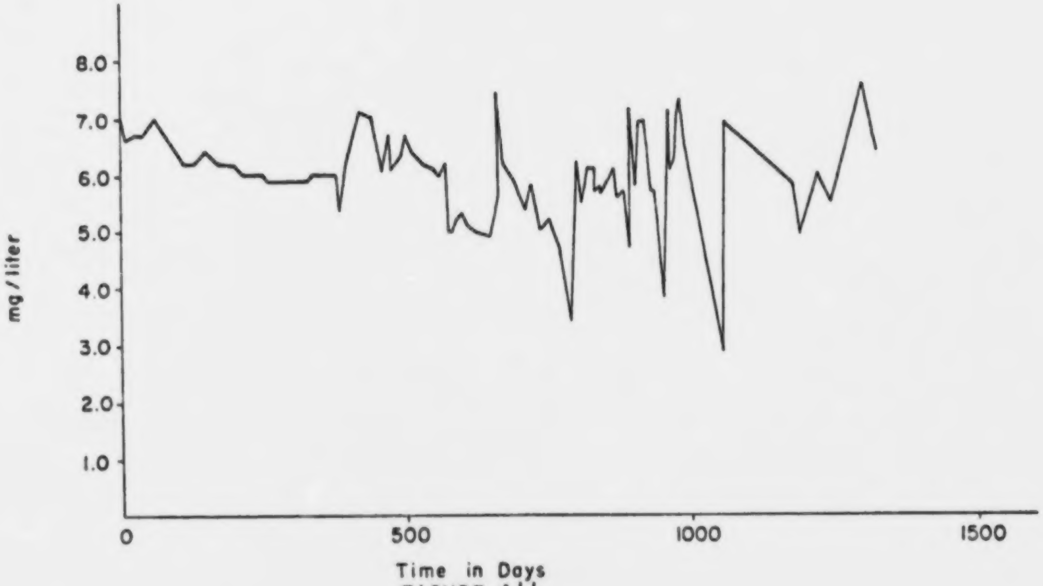
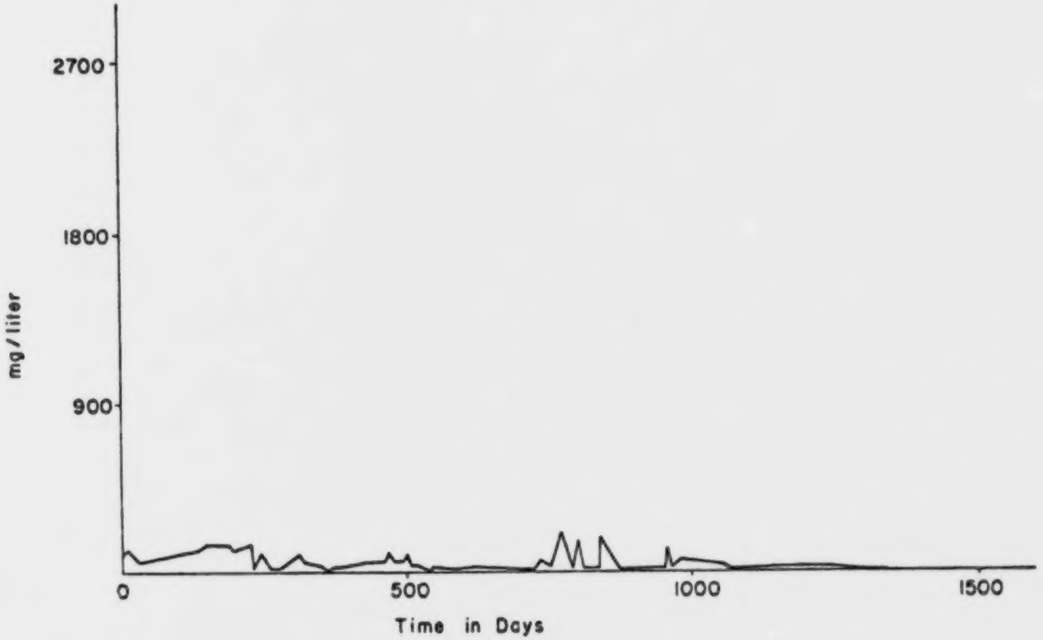


FIGURE 144



CHEMICAL OXYGEN DEMAND
TEST WELL No. 3

FIGURE 145

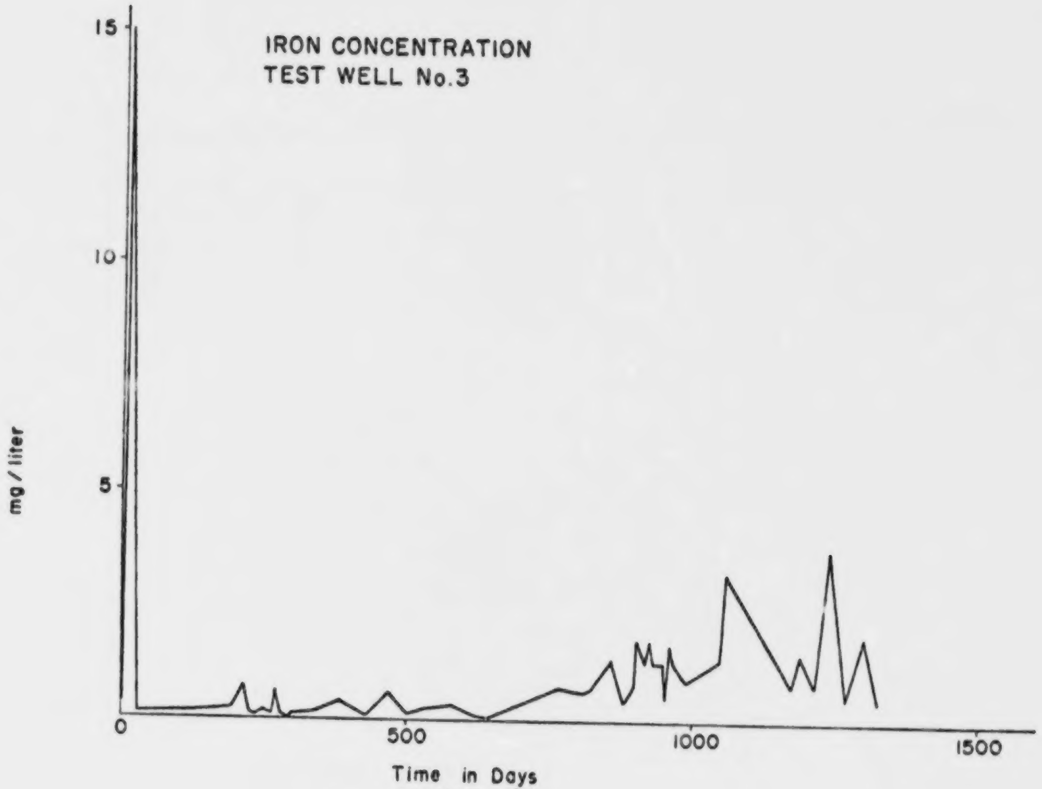

IRON CONCENTRATION
TEST WELL No.3
mg / liter
15
10
5
0
500
1000
1500
Time in Days

FIGURE 146

TOTAL DISSOLVED SOLIDS
TEST WELL No. 3

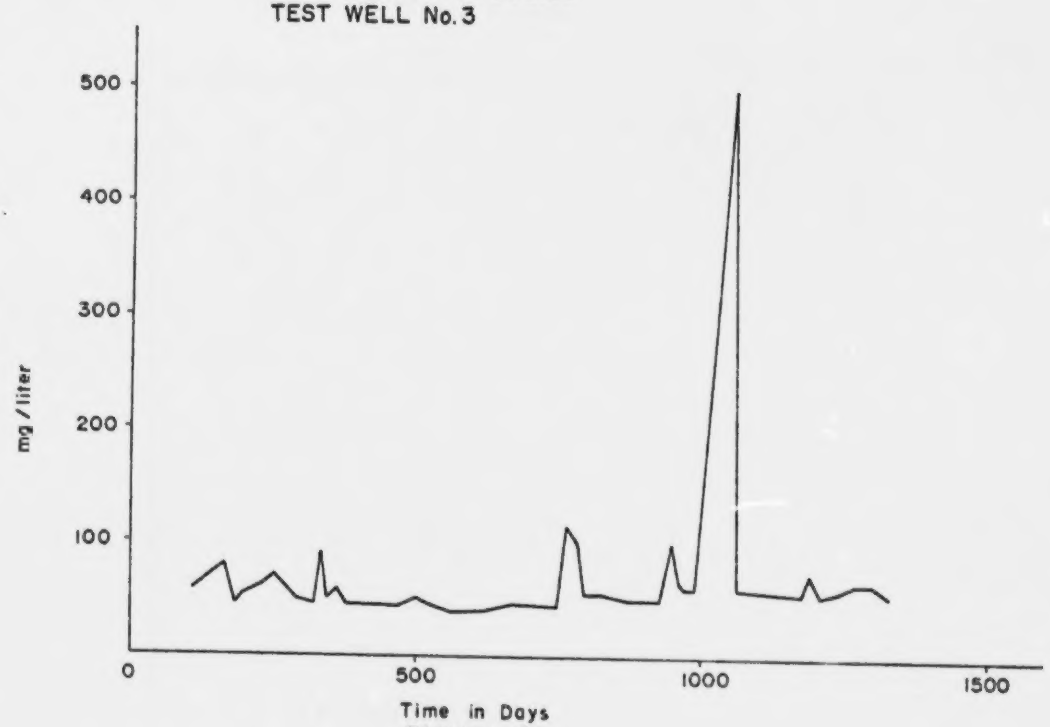


FIGURE 147

CHLORIDE
TEST WELL No. 3

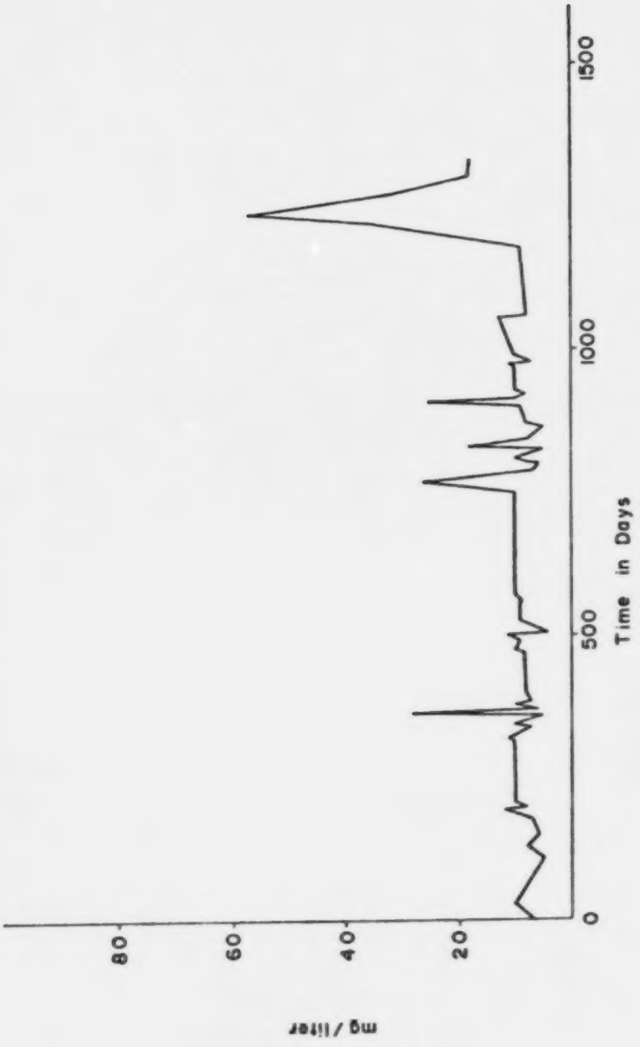


FIGURE 148

SODIUM
TEST WELL No. 3

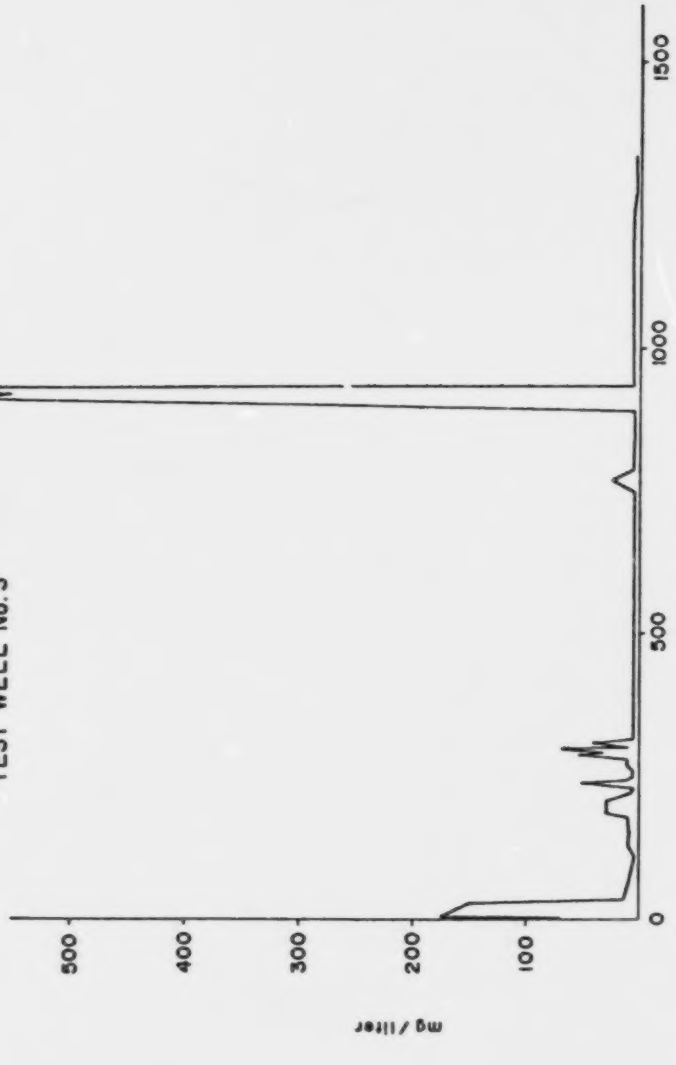


FIGURE 149

Chloride - Generally chlorides do not exceed 20 mg/l although a rapid rise occurs during the flood period to 200 mg/l. Another rise occurs at approximately 1200 days into the test, being more pronounced in well 13 than in well 12. In well 13 a peak of approximately 200 mg/l is attained. This latter peak corresponds to the second peak present in the curves for the other parameters monitored.

Sodium - Sodium concentrations are generally less than 20 mg/l. A peak over 800 mg/l for well number 12 and over 700 mg/l for well number 13 occurs about 900 days into the test. This time corresponds to the period of flooding to bring the system to field capacity and reflects on the inability of the system to absorb large increases in water flow.

Well 3 -

Well number 3 is located down gradient from the field facility and immediately outside the refuse.

pH - pH range for the entire period falls within the range of background water quality data and does not show any significant influences due to leachate from the refuse.

COD - COD range for the entire period falls within the range of background water quality data and does not show any significant influences due to leachate from the refuse.

Iron - Iron concentrations were within background levels until approximately 800 days into the test. Thereafter values increased to approximately 4 mg/l and then varied with time. While iron concentrations exceeded background levels, the increases are much less than pure leachate concentrations.

Total Dissolved Solids - Total dissolved solids range between 50 and 100 mg/l. At approximately 1000 days into the test the value increases to 500 mg/l. The total dissolved solids are higher than reported background values but their overall limited variations suggest more background levels than an effect of leachate from the refuse.

Chloride - Except for an increase in chloride concentration to 55 mg/l approximately 1200 days into the test, values generally fall within background ranges.

Sodium - Sodium concentrations increase to approximately 650 mg/l between 900 to 1000 days into the test. However, during the remainder of the test period, concentrations fall within background values ranges.

Field Shallow Well Study

Curves are presented for the E, SI, SF, WI and WF series in Figures 150 through 177. With a couple of exceptions, the curves are for TDS, pH, iron, chloride, sodium and COD.

The SI series, which is down ground water gradient from the refuse cell, clearly shows the layer influence with depth. Concentrations of each contaminant decreases with increasing depth to approximately background concentration levels.

The SF series further down gradient than the SI series shows little, if any, change from background concentration levels.

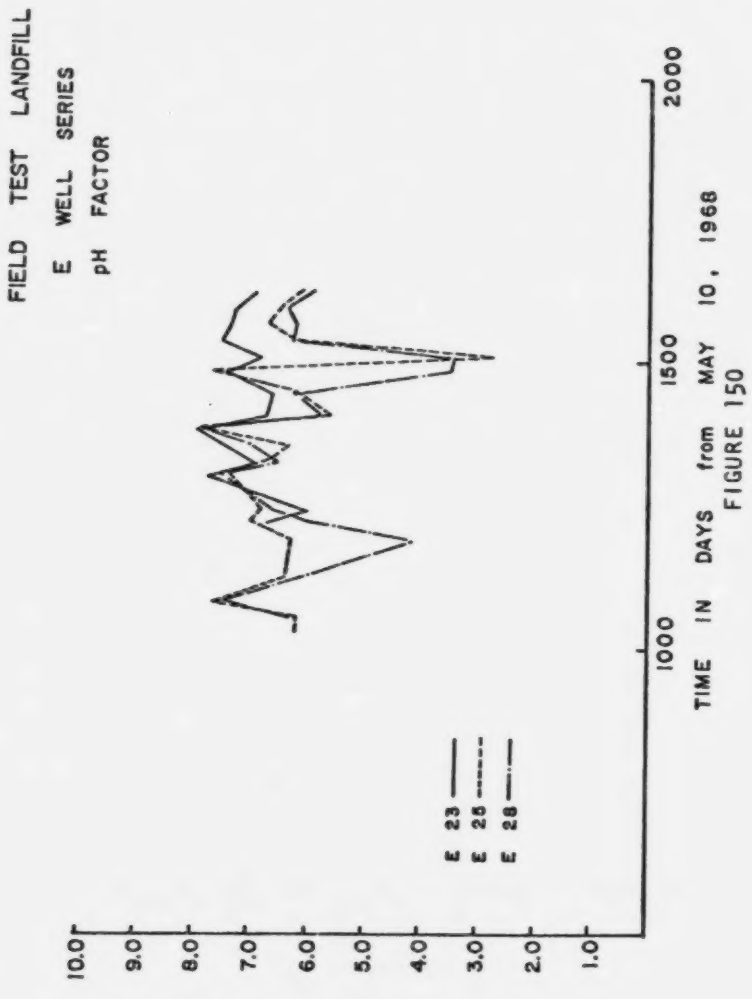
The E series is adjacent to the test cell, but somewhat down gradient. This series shows the effect of lateral as well as vertical dispersion. Concentrations of the various contaminants are higher than background but less than found in the SI series at the same depths.

The WI and WF series patterns are similar to those for the SI and SF series and also reflect lateral as well as vertical dispersion effects.

Ground Water Total Dissolved Solids Study

Figures 178 through 182 compare total dissolved solids for selected deep and shallow well series. The purpose of these comparisons is to establish layer effect within the ground water system.

The results of these comparisons clearly indicate that such layering exists and can be defined with relative ease. For example, the comparison of TDS for well 4, the WI shallow well series, and the SI shallow well series, indicates a high buildup of TDS at the shallow depths with background concentrations at the greater depths.



FIELD TEST LANDFILL
E WELL SERIES
pH FACTOR

FIGURE 150

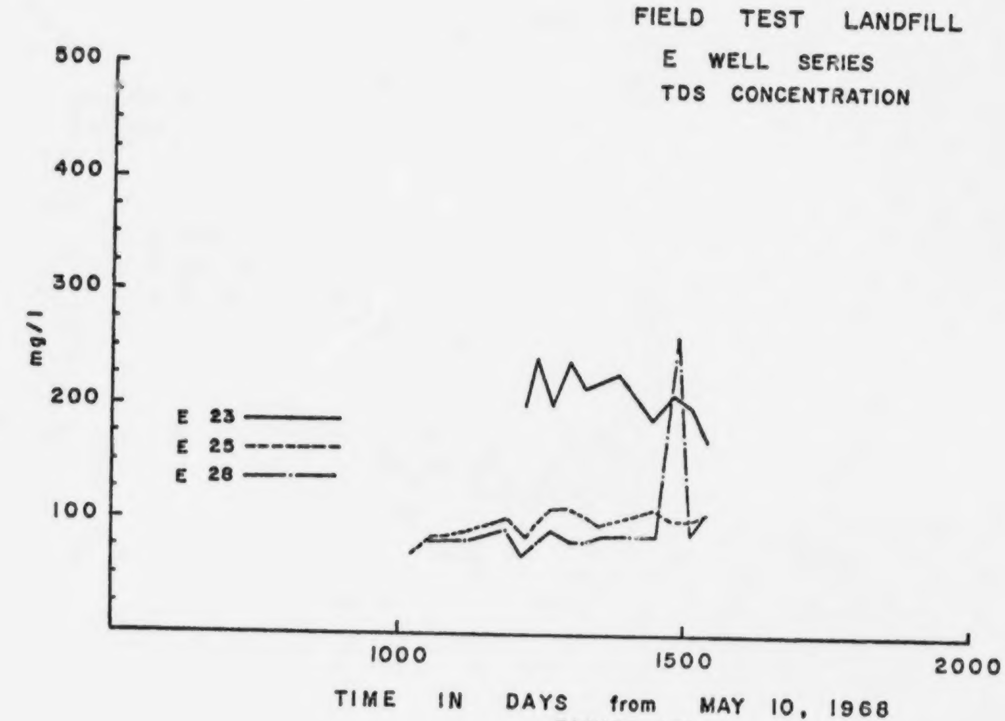
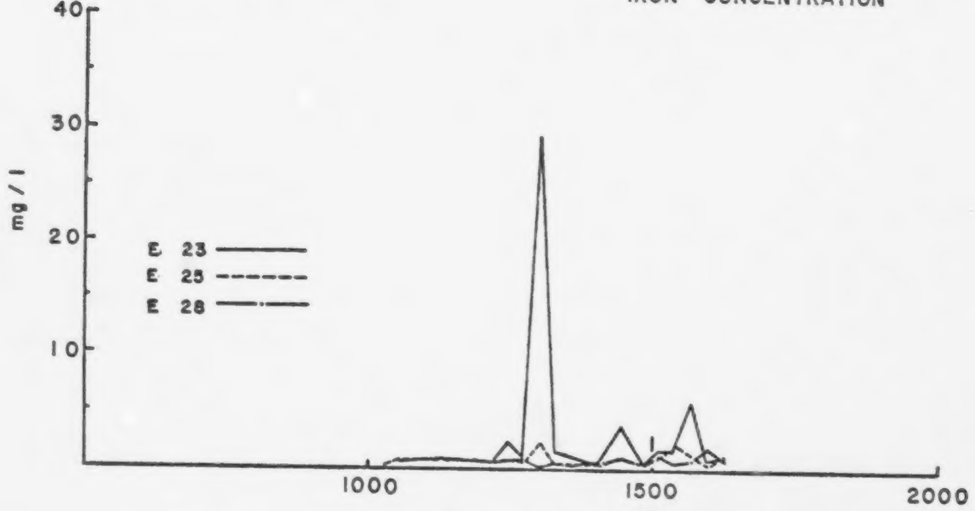

FIELD TEST LANDFILL
E WELL SERIES
TDS CONCENTRATION
500
400
300
200
100
mg/l
E 23
E 25
E 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 151

FIELD TEST LANDFILL

E WELL SERIES

IRON CONCENTRATION



TIME IN DAYS from MAY 10, 1968

FIGURE 152

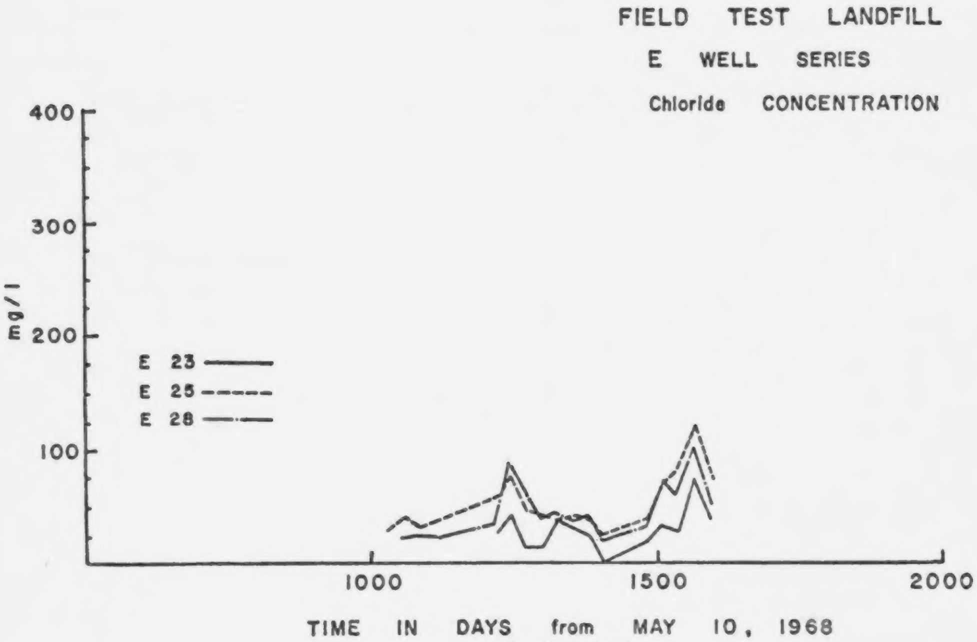

FIELD TEST LANDFILL
E WELL SERIES
Chloride CONCENTRATION
400
300
200
100
mg/l
E 23
E 25
E 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 153

FIELD TEST LANDFILL
E WELL SERIES
Na CONCENTRATION

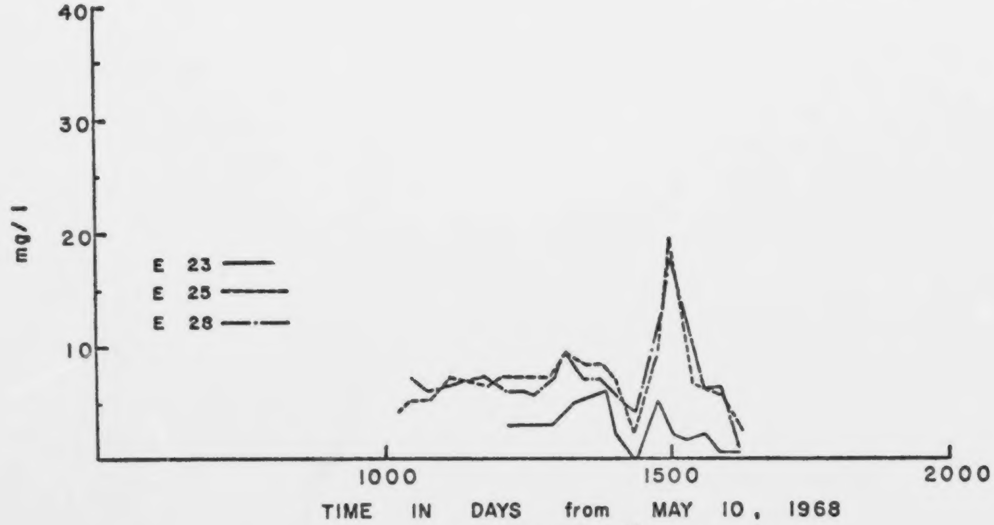


FIGURE 154

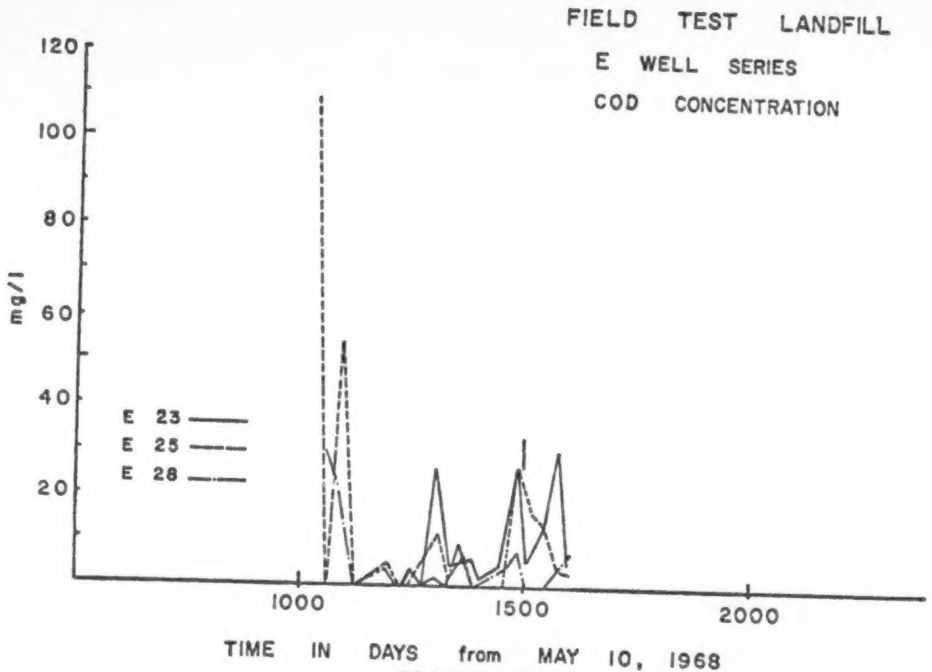

FIELD TEST LANDFILL
E WELL SERIES
COD CONCENTRATION
mg/l
120
100
80
60
40
20
E 23
E 25
E 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 155

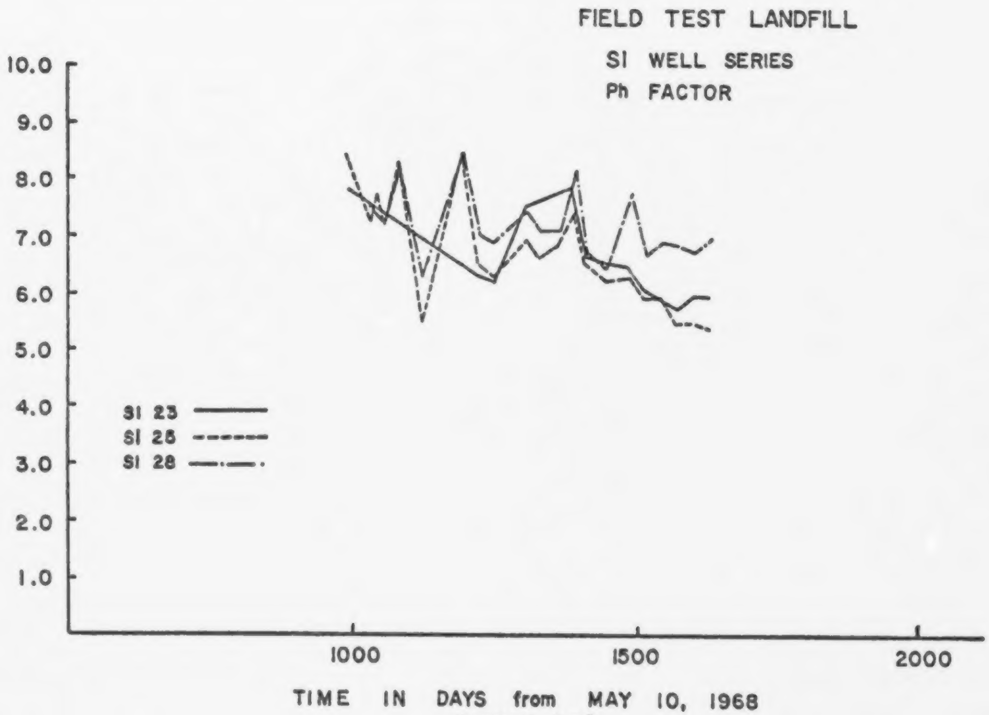

FIELD TEST LANDFILL
SI WELL SERIES
Ph FACTOR
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
SI 23
SI 26
SI 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 156

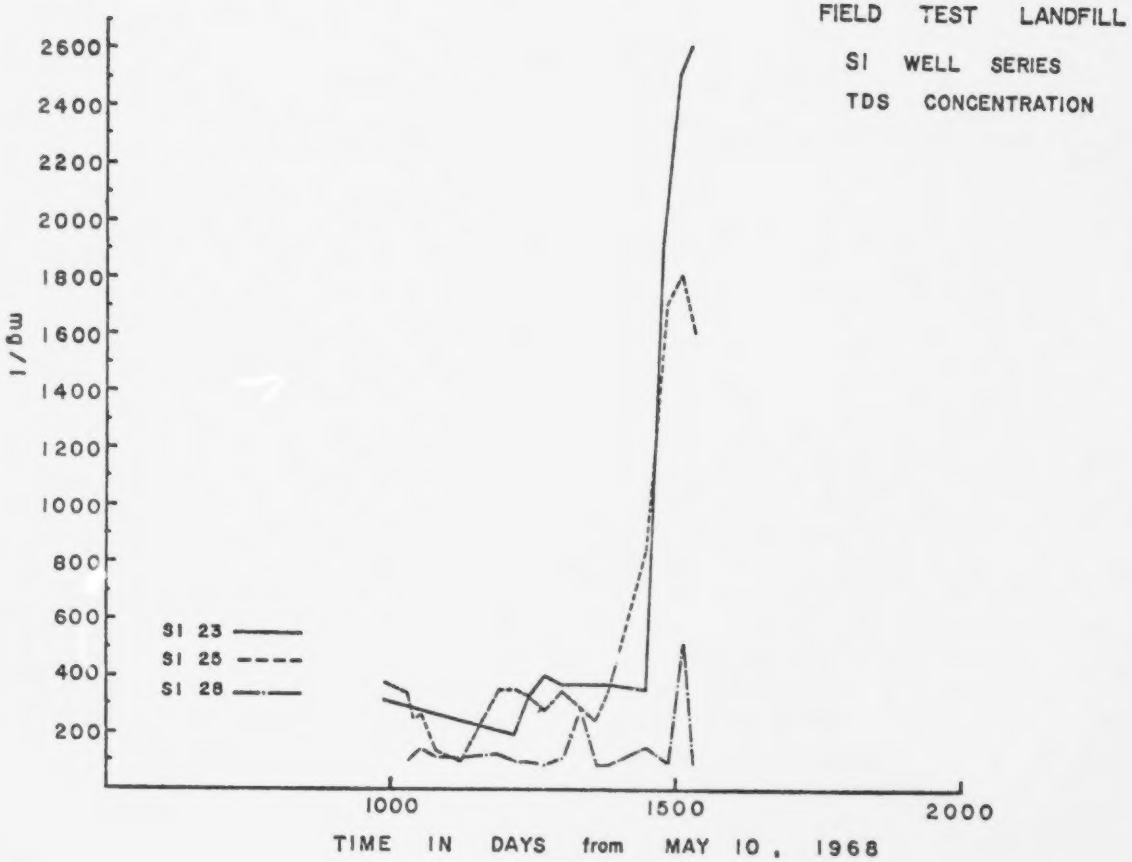

FIELD TEST LANDFILL
SI WELL SERIES
TDS CONCENTRATION
mg/l
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
SI 23
SI 25
SI 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 157

FIELD TEST LANDFILL
SI WELL SERIES
Iron CONCENTRATION

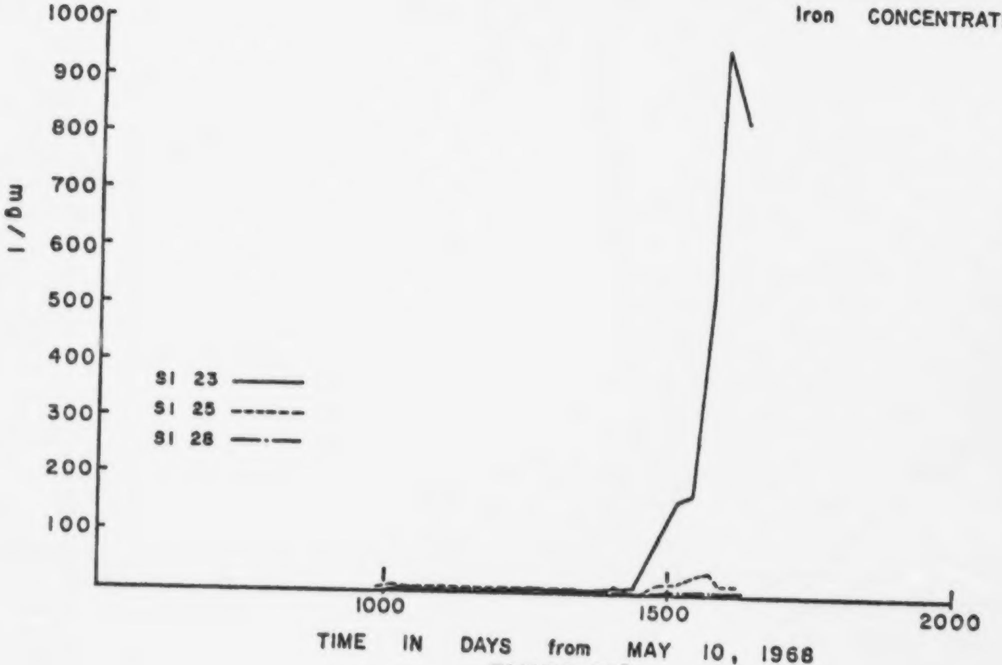
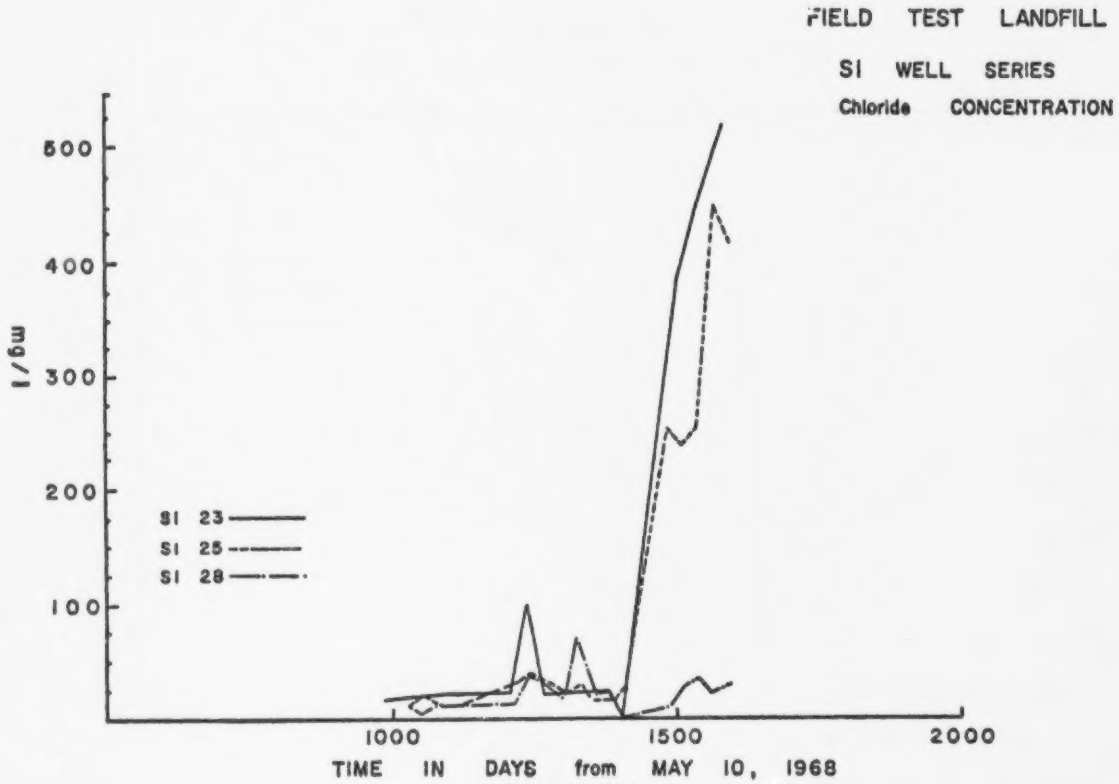


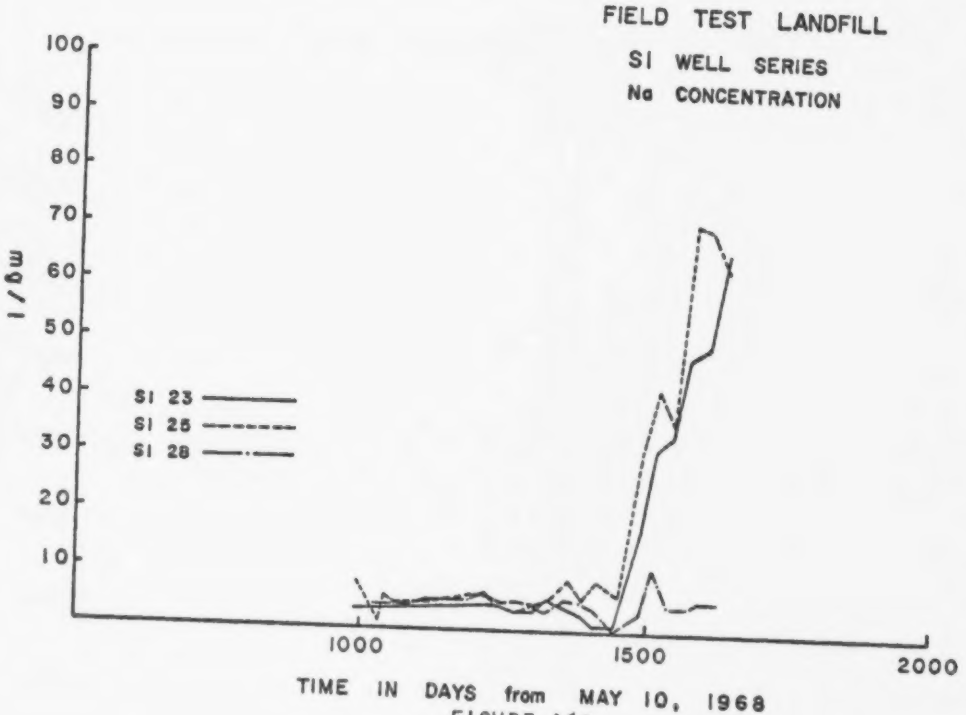
FIGURE 158


FIELD TEST LANDFILL

SI WELL SERIES

Chloride CONCENTRATION

FIGURE 159

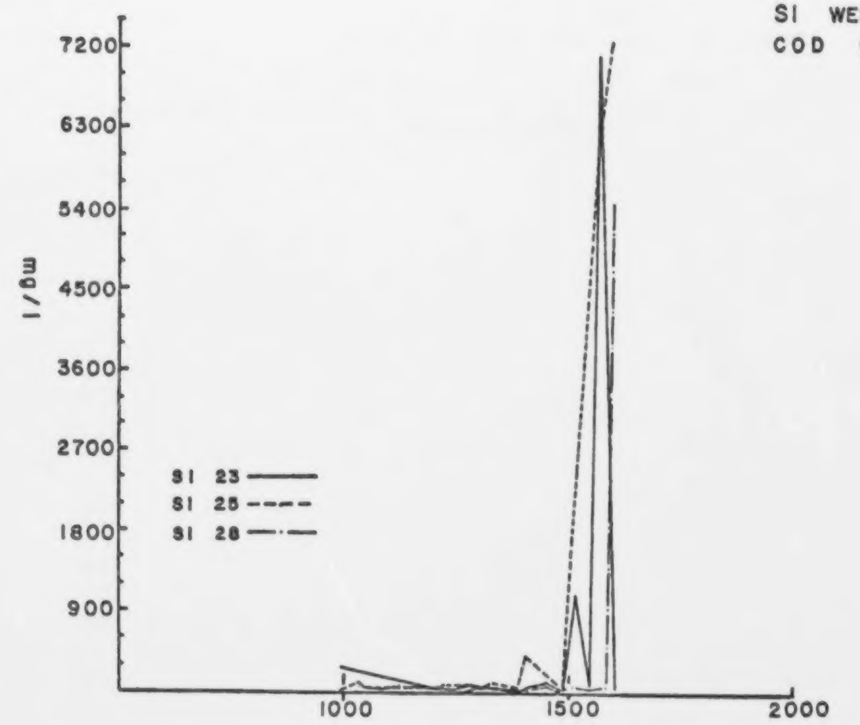


FIELD TEST LANDFILL

SI WELL SERIES

Na CONCENTRATION

FIGURE 160



FIELD TEST LANDFILL

SI WELL SERIES

COD CONCENTRATION

TIME IN DAYS from MAY 10, 1968

FIGURE 161

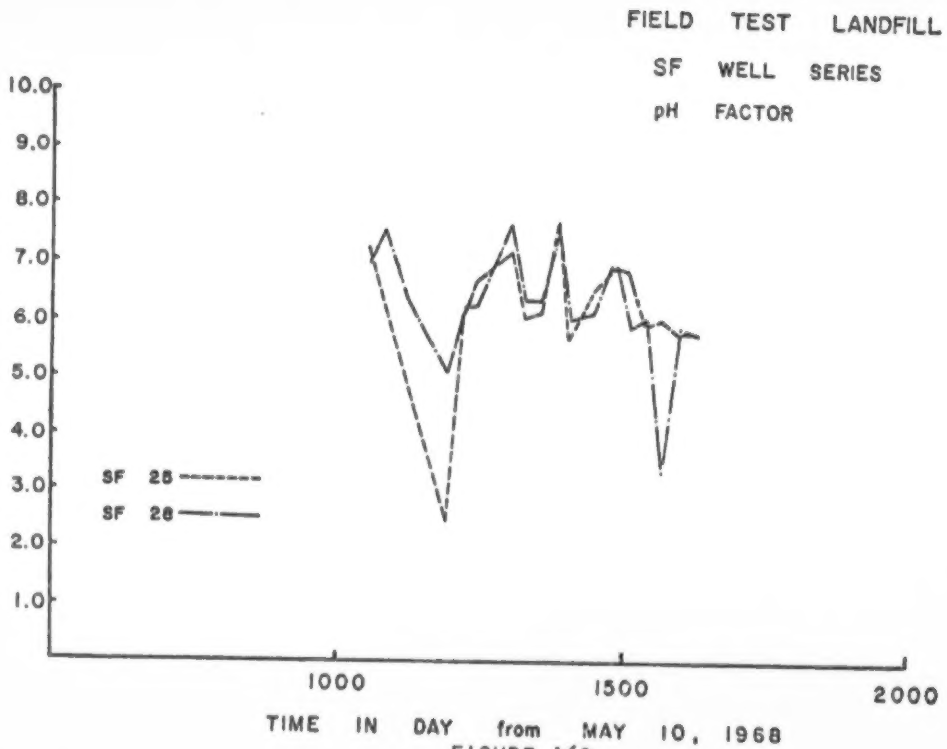

FIELD TEST LANDFILL
SF WELL SERIES
pH FACTOR
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
SF 28
SF 28
1000
1500
2000
TIME IN DAY from MAY 10, 1968

FIGURE 162

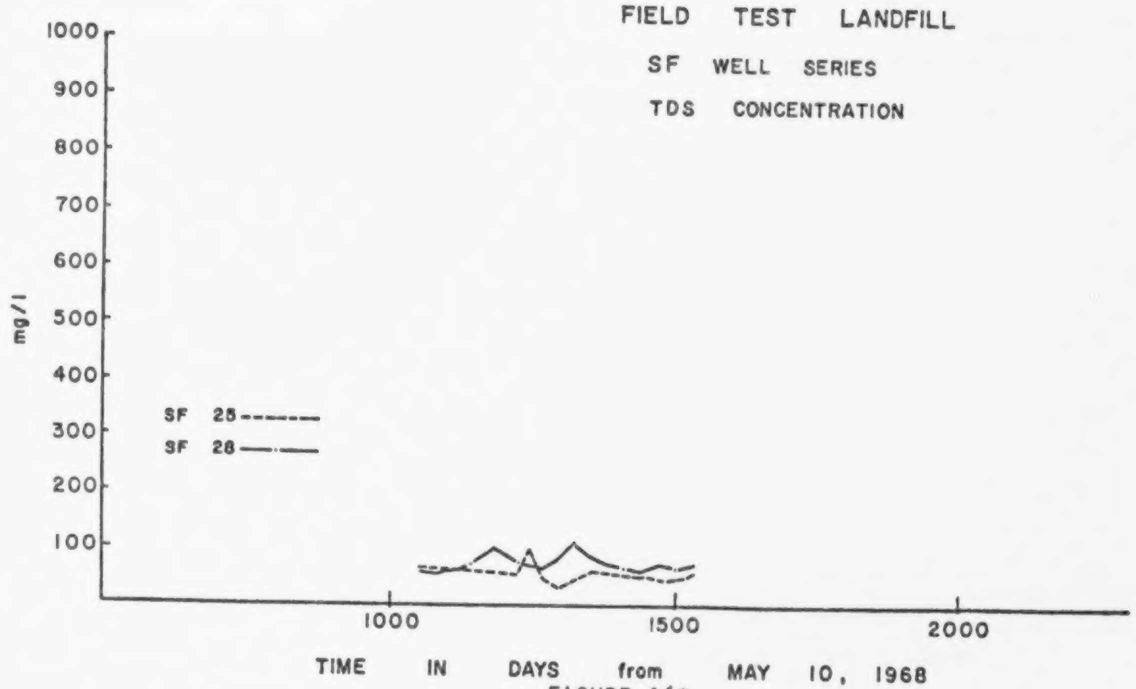

FIELD TEST LANDFILL
SF WELL SERIES
TDS CONCENTRATION
mg/l
1000
900
800
700
600
500
400
300
200
100
SF 25
SF 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 163

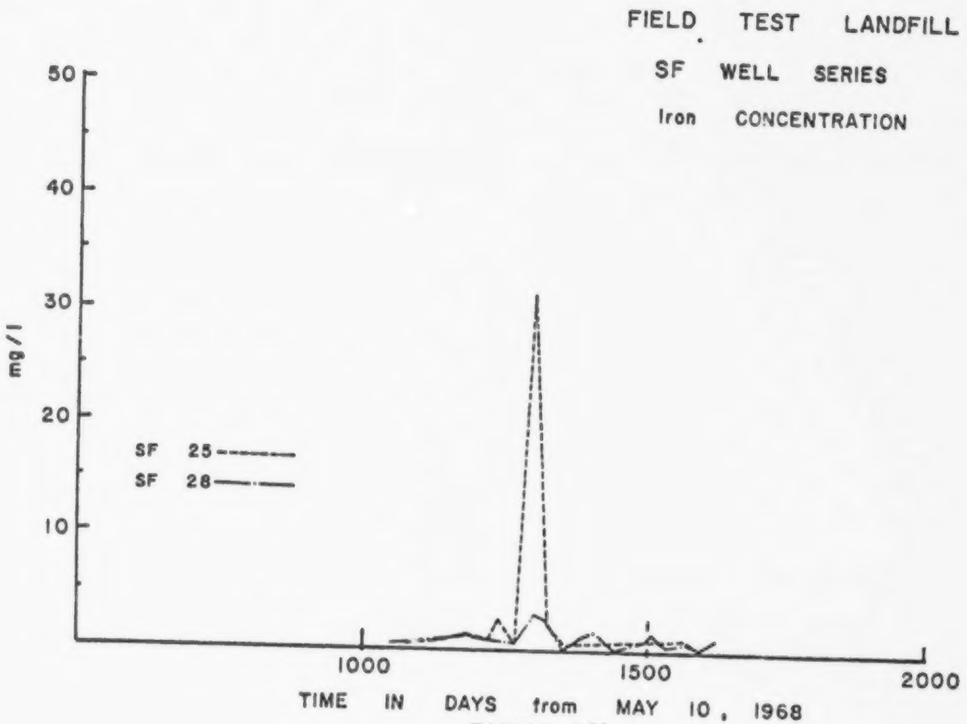
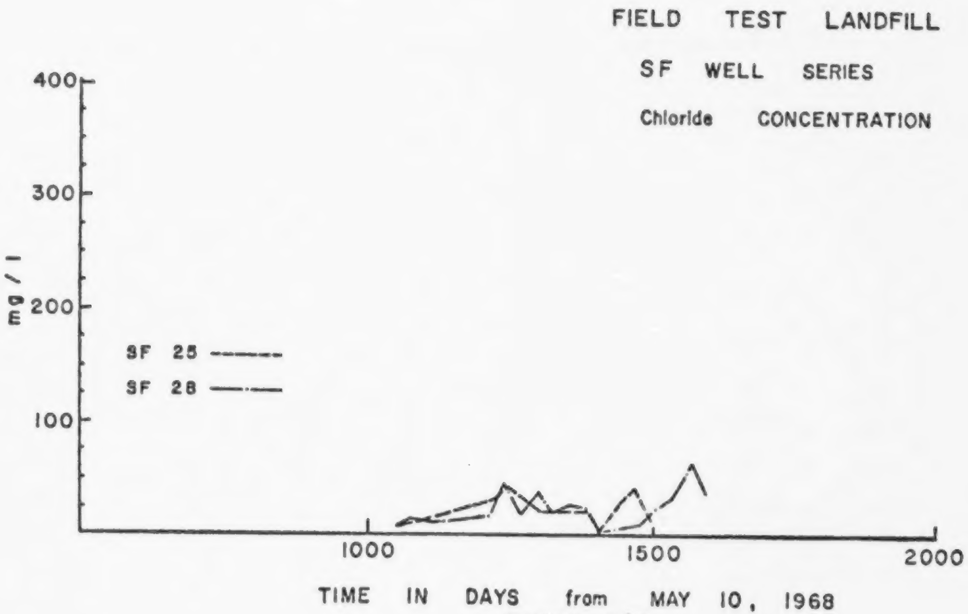

FIELD TEST LANDFILL
SF WELL SERIES
Iron CONCENTRATION
mg/l
50
40
30
20
10
SF 25
SF 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 164



FIELD TEST LANDFILL

SF WELL SERIES

Chloride CONCENTRATION

FIGURE 165

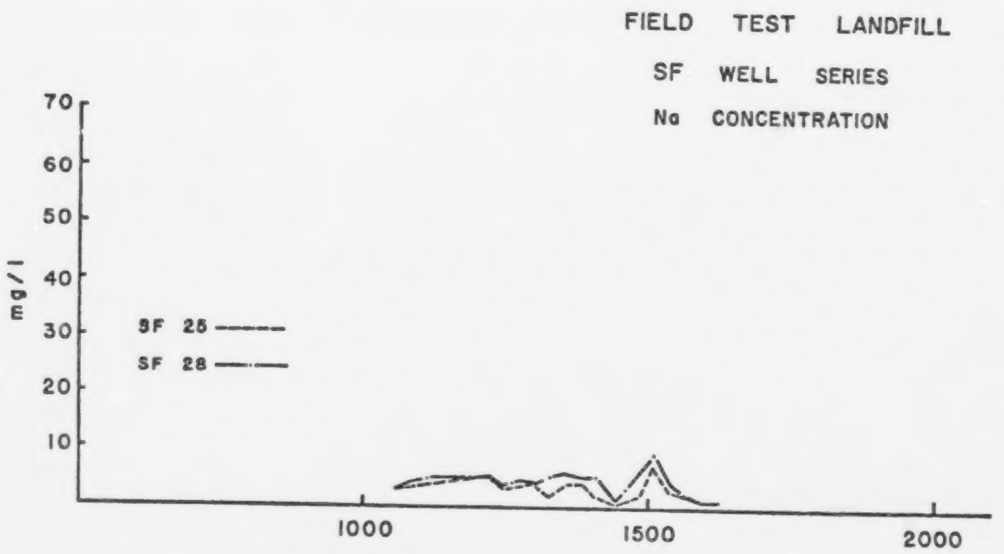

FIELD TEST LANDFILL
SF WELL SERIES
Na CONCENTRATION
mg/l
70
60
50
40
30
20
10
SF 25
SF 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 166

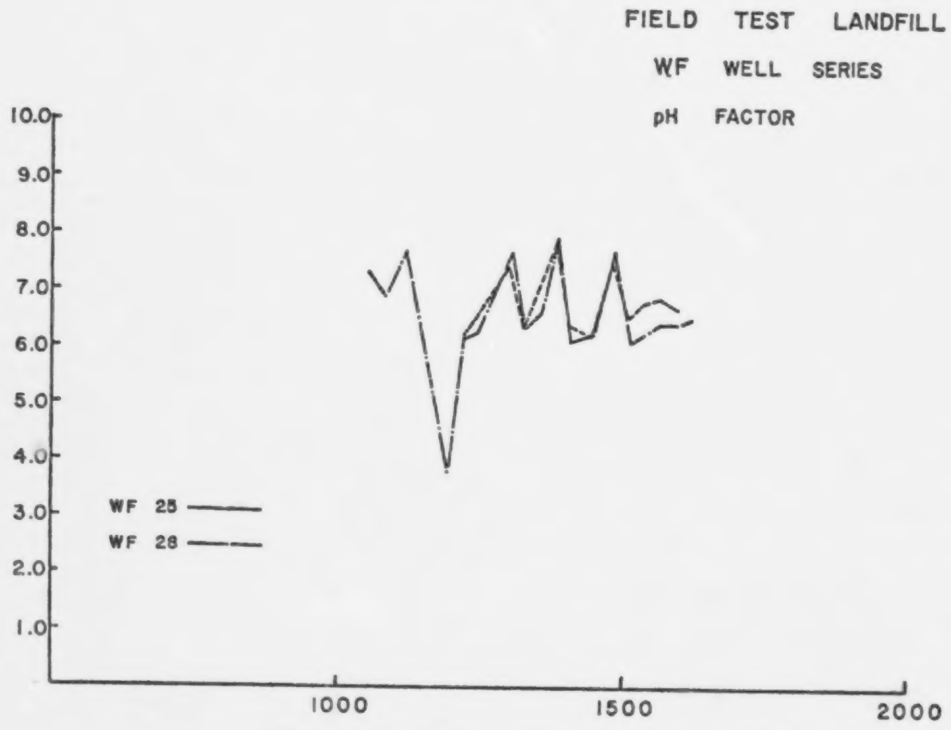

FIELD TEST LANDFILL
WF WELL SERIES
pH FACTOR

FIGURE 167

FIELD TEST LANDFILL

WF WELL SERIES

TDS CONCENTRATION

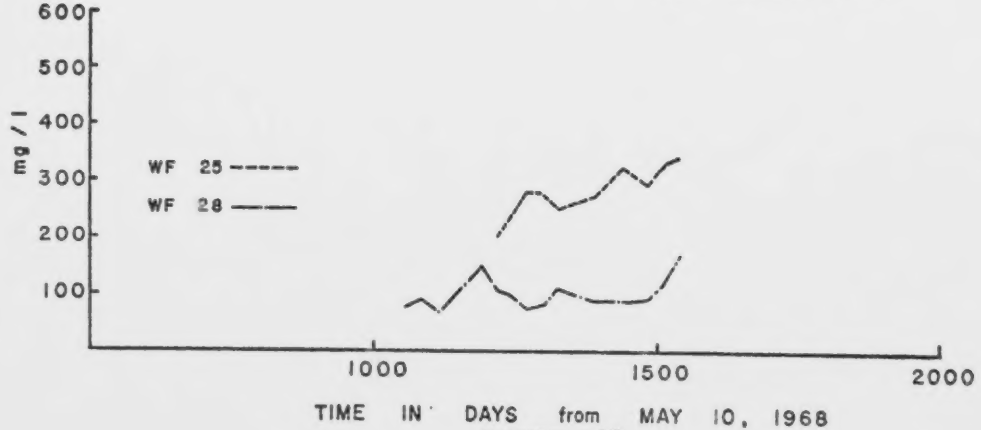


FIGURE 168

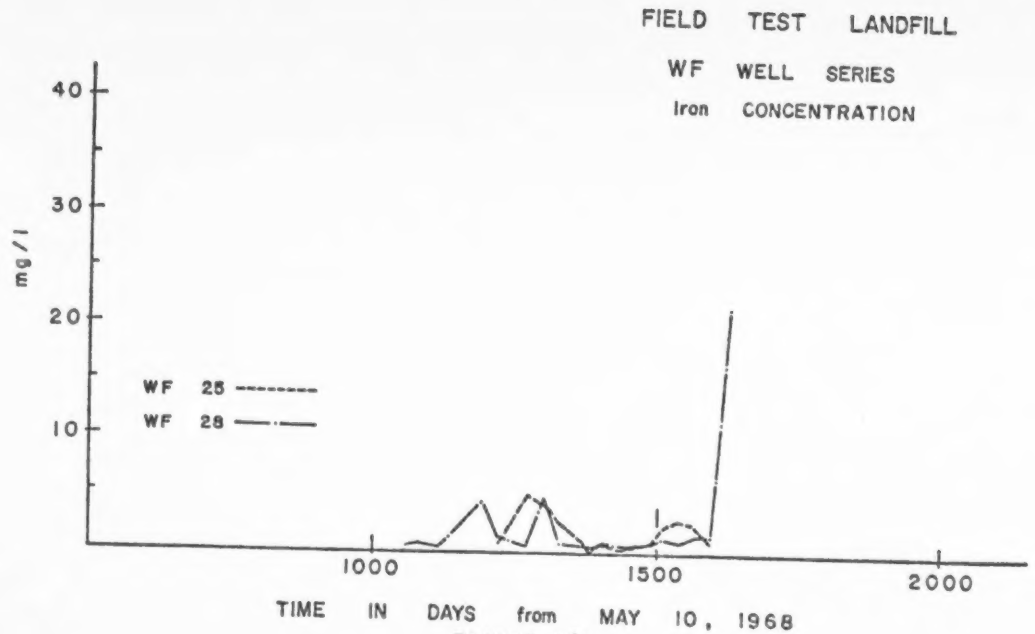
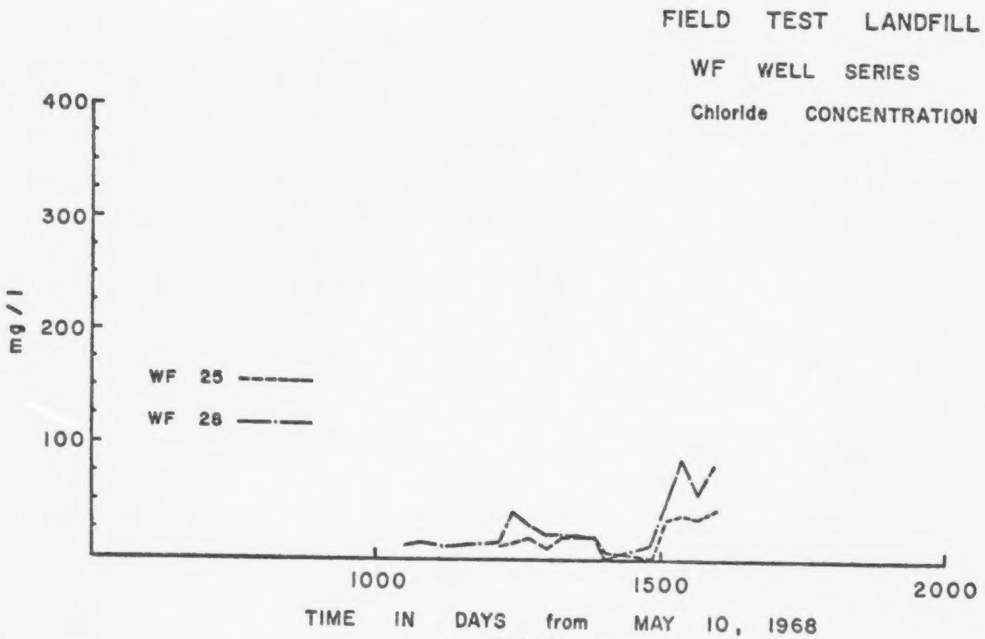

FIELD TEST LANDFILL
WF WELL SERIES
Iron CONCENTRATION
mg/l
40
30
20
10
WF 25 --------
WF 28 —·—
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 169


FIELD TEST LANDFILL

WF WELL SERIES

Chloride CONCENTRATION

FIGURE 170

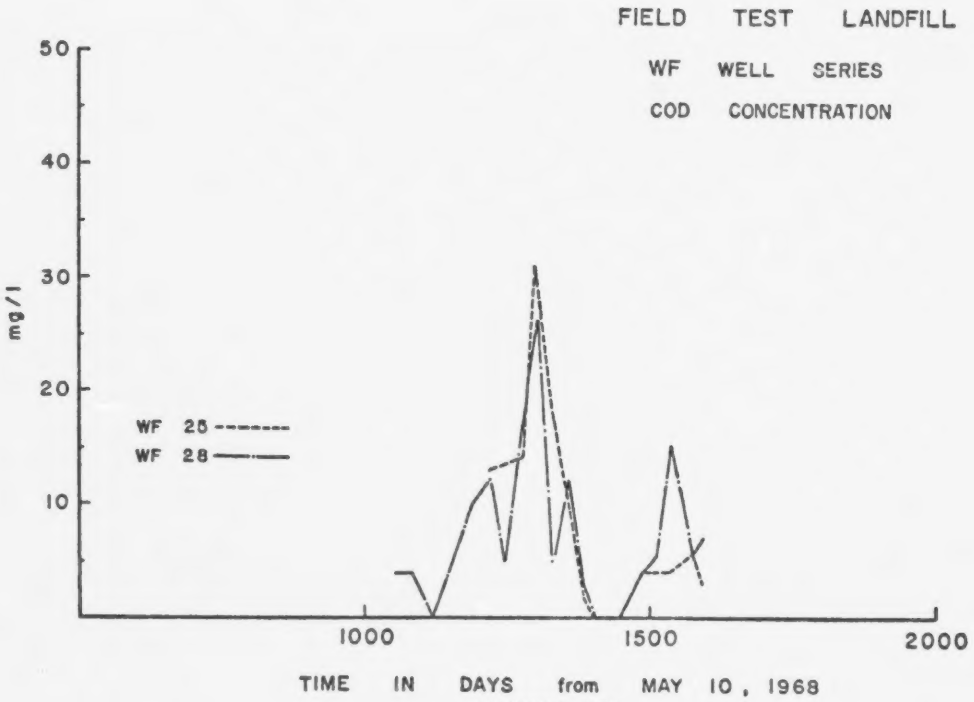

FIELD TEST LANDFILL
WF WELL SERIES
COD CONCENTRATION
50
40
30
20
10
mg/l
WF 25
WF 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 171

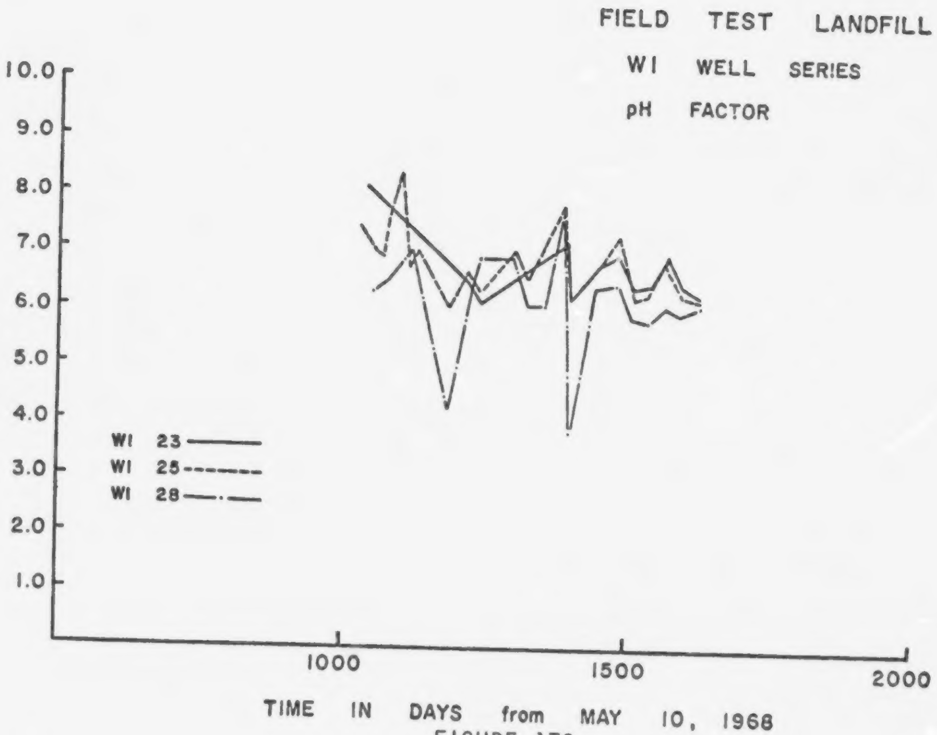
FIELD TEST LANDFILL
WI WELL SERIES
pH FACTOR
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
WI 23
WI 25
WI 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 172

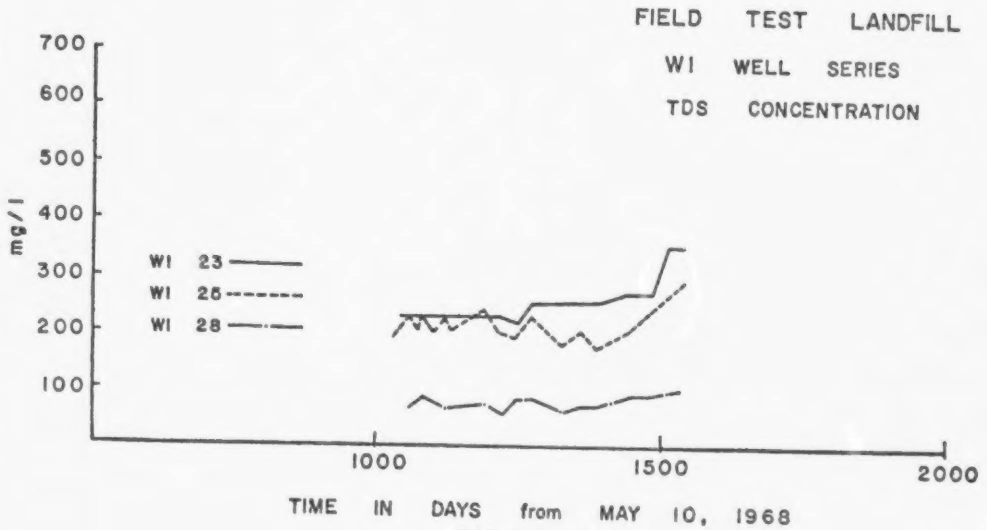

FIELD TEST LANDFILL
WI WELL SERIES
TDS CONCENTRATION
mg/l
700
600
500
400
300
200
100
WI 23
WI 25
WI 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 173

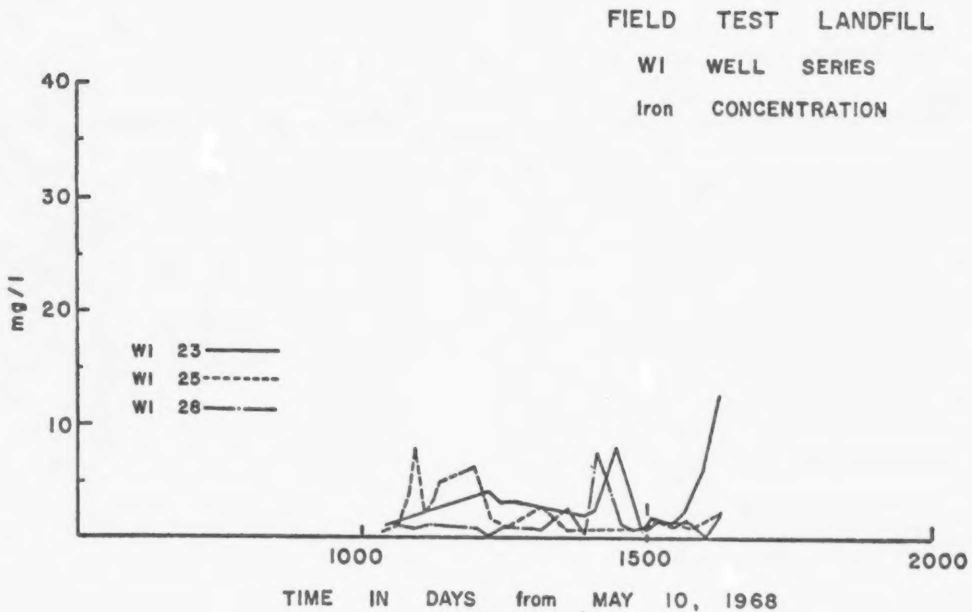

FIELD TEST LANDFILL
WI WELL SERIES
Iron CONCENTRATION
mg/l
40
30
20
10
WI 23
WI 25
WI 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 174

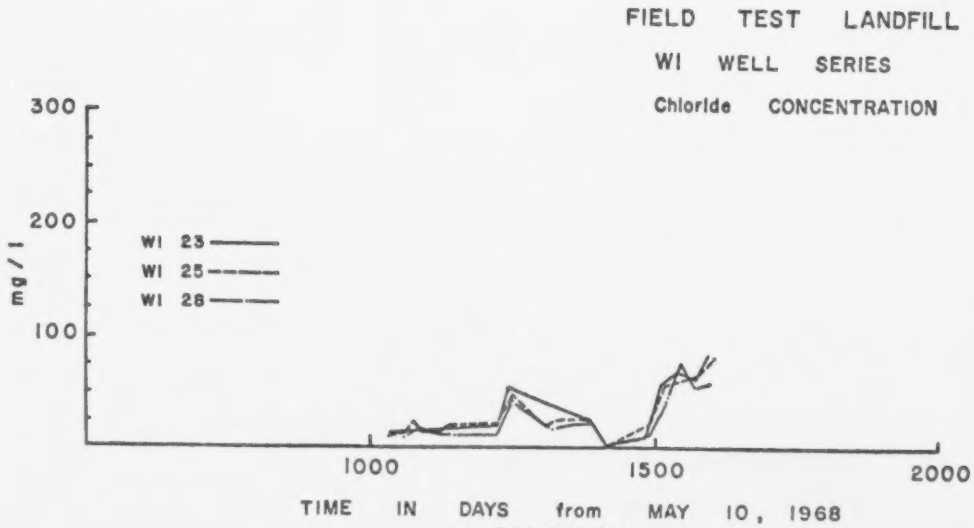

FIELD TEST LANDFILL
WI WELL SERIES
Chloride CONCENTRATION
300
200
100
mg / l
WI 23
WI 25
WI 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 175

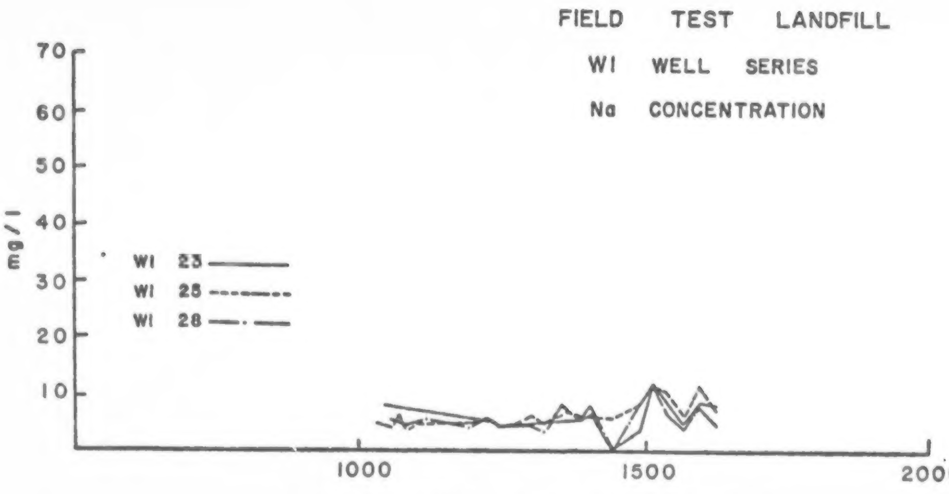
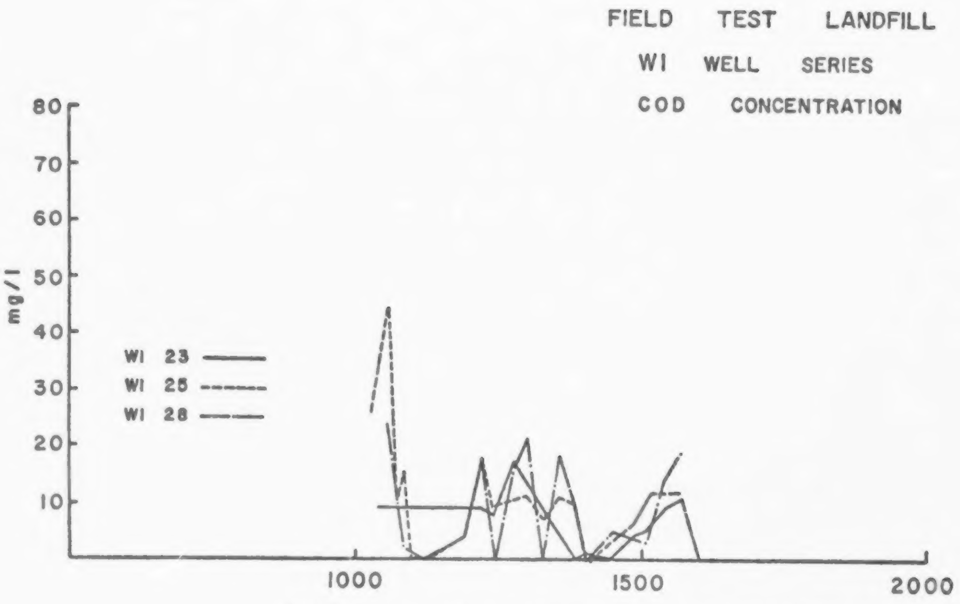

FIELD TEST LANDFILL
WI WELL SERIES
Na CONCENTRATION
mg/l
70
60
50
40
30
20
10
WI 23
WI 25
WI 28
1000
1500
2000
TIME IN DAYS from MAY 10, 1968

FIGURE 176


FIELD TEST LANDFILL

WI WELL SERIES

COD CONCENTRATION

FIGURE 177

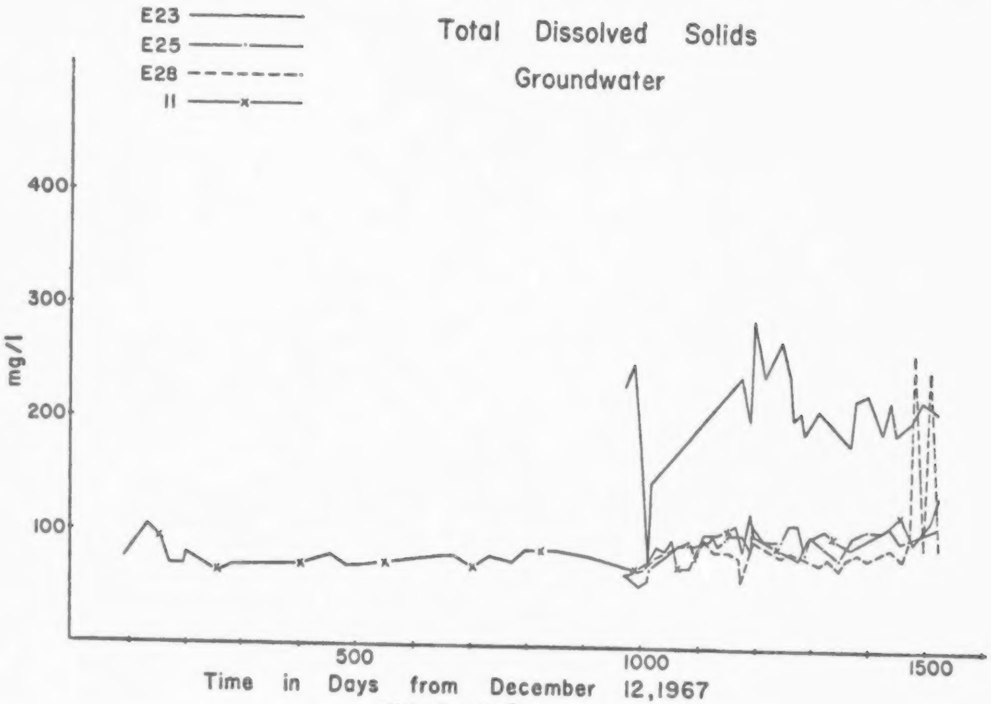
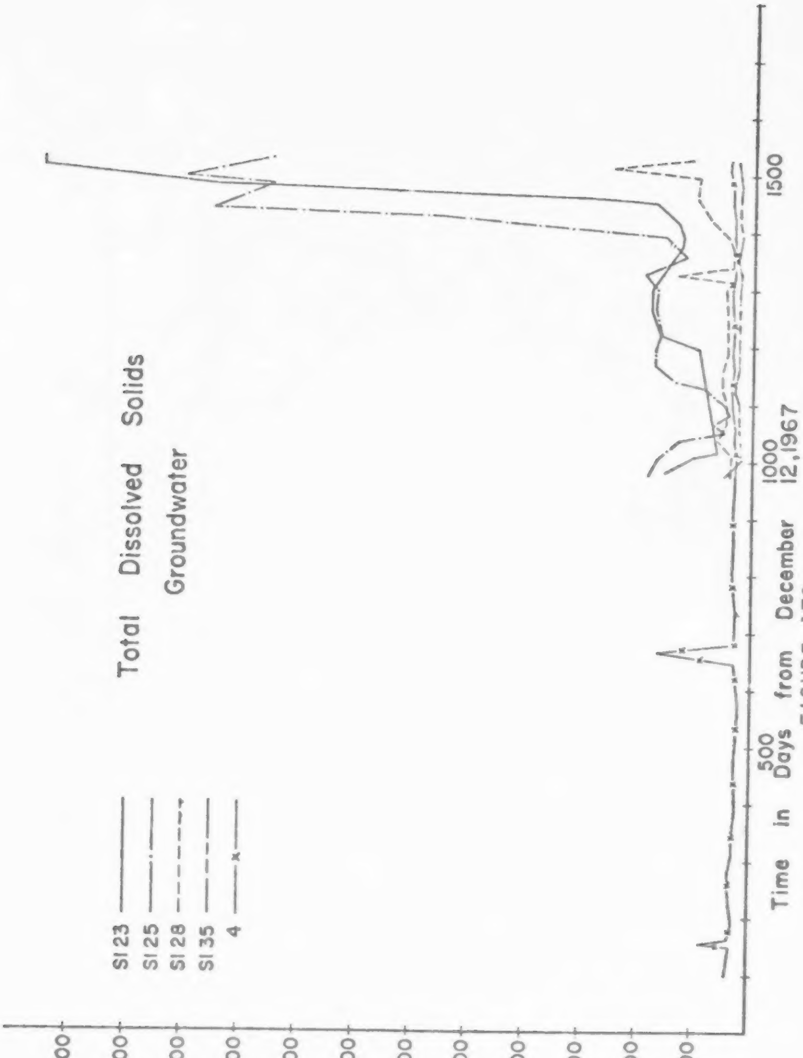

Total Dissolved Solids
Groundwater
E23
E25
E28
11
mg/l
400
300
200
100
500
1000
1500
Time in Days from December 12,1967

FIGURE 178



Total Dissolved Solids

Groundwater

FIGURE 179

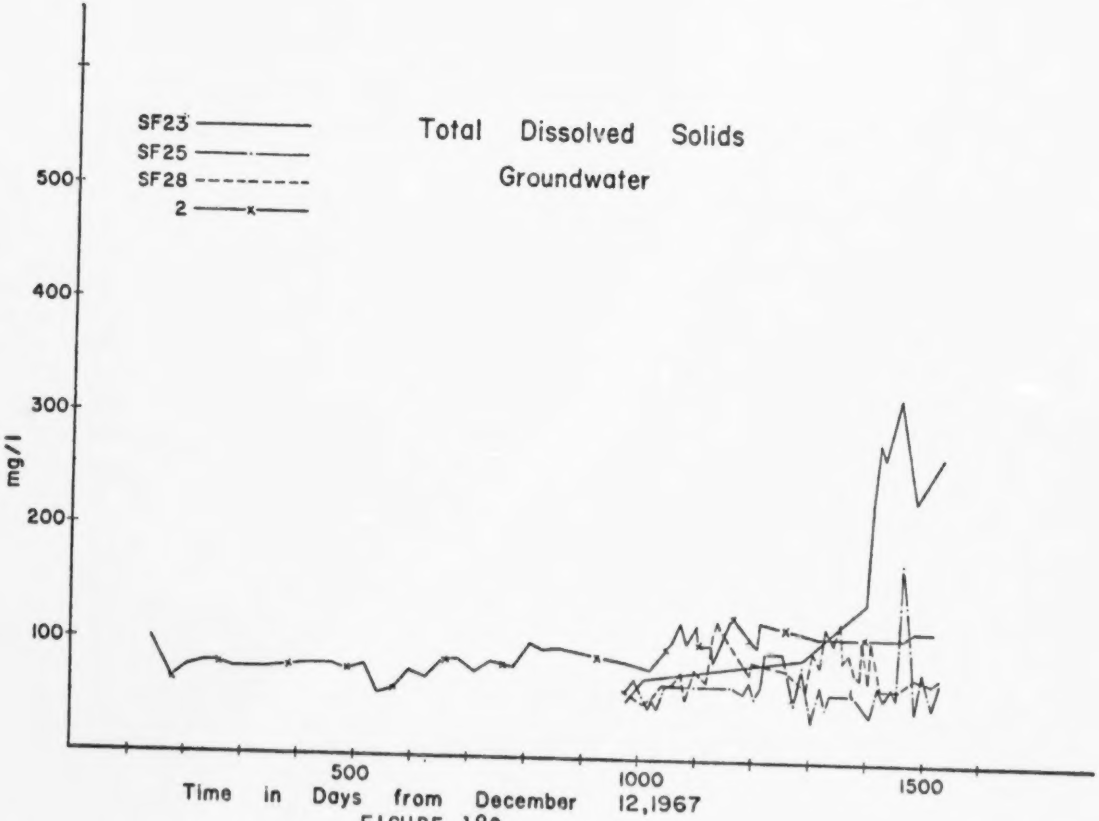

SF23
SF25
SF28
2
Total Dissolved Solids
Groundwater
500
400
300
200
100
mg/l
500
1000
1500
Time in Days from December 12,1967

FIGURE 180

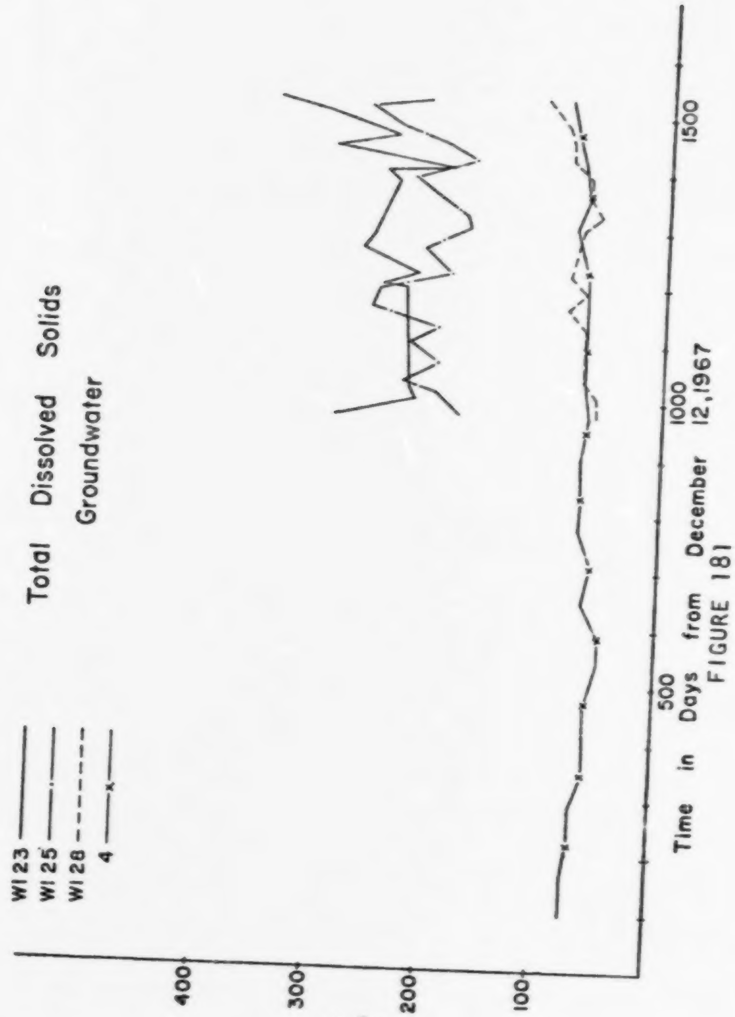

Total Dissolved Solids
Groundwater
WI 23
WI 25
WI 28
4
mg/l
400
300
200
100
500
1000
1500
Time in Days from December 12,1967

FIGURE 181

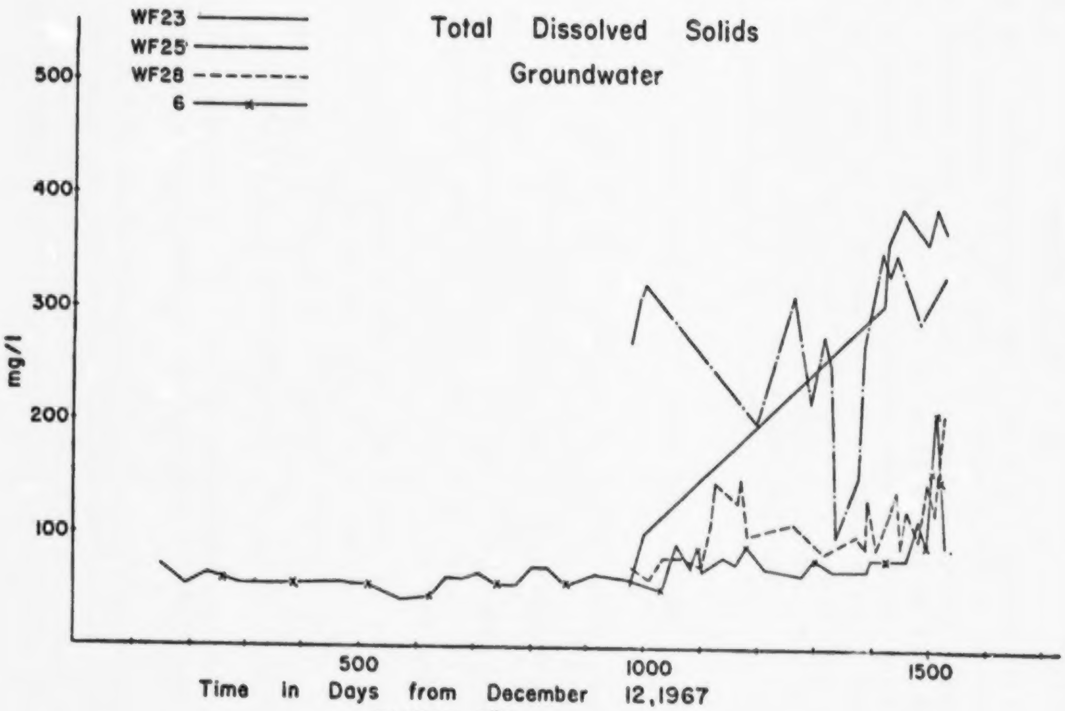

Total Dissolved Solids
Groundwater
WF23
WF25
WF28
6
mg/l
500
400
300
200
100
500
1000
1500
Time in Days from December 12,1967

FIGURE 182

SECTION 5

THEORETICAL ANALYSIS OF LEACHATE POLLUTANT MOVEMENT IN GROUND WATER

Leachate ground water interaction is controlled by a complex system of interactions between (1) the leachate discharged from the solid waste disposal site, (2) the ground water system, and (3) solid matrix of the subsurface soils. Discussed in this section are relationships between travel of leachate pollutants from a solid waste disposal site and the major hydrologic parameters that characterize the subsurface water movement. Non-dimensional parameters are used in defining the patterns of leachate pollutant migration in the ground water system and for different leachate source patterns.

The parametric study had four (4) major objectives. These were:

(a) To predict patterns of subsurface leachate pollutant movement in non-dimensional form, for various hydrologic parameters which represent field conditions. The resulting patterns could serve as criteria for either site selection or evaluating the impact of a particular leachate pollution source on a subsurface environment.

(b) To compare theoretical leachate pollution patterns with the results from an experimental solid waste disposal site. This comparison had as its objective the determination of the validity of using mathematical and computer models for making such predictions.

(c) To determine relative changes in leachate pollutant profiles due to changes in hydrologic parameters.

(d) To evaluate the different physical and chemical mechanisms involved in the migration of leachate pollutants from a solid waste disposal site, and to evaluate the relative importance of these mechanisms.

The Mathematical Model

The mathematical model used in this study is based on solving second-order partial differential equations which represent the dispersion of leachate from a solid waste disposal site into an unconfined ground water system. The general equations which define the behavior for both the horizontal and vertical domains can be shown to be:

$$\frac{\partial c}{\partial t} = Dx \frac{\partial^2 c}{\partial x^2} + Dy \frac{\partial^2 c}{\partial y^2} - u \frac{\partial c}{\partial x} - v \frac{\partial c}{\partial y} - f\ (c)$$

$$\frac{\partial c}{\partial t} = Dx \frac{\partial^2 c}{\partial x^2} + Dz \frac{\partial^2 c}{\partial z^2} - u \frac{\partial c}{\partial x} - w \frac{\partial c}{\partial z} - f\ (c)$$

These equations contain the different parameters which are involved in the mass transport processes of simultaneous diffusion, convection, and chemical reaction. The significant parameters are:

(a) The Leachate Pollutant Concentration (c)

The leachate pollutant which discharges from the solid waste disposal site can be expressed in concentrations of anions and cations in excess of concentrations of the corresponding ions in the background ground water conditions. For this study total inorganic dissolved solids (TDS) were selected as the indicator of the leachate pollutant load in the ground water system. The average value of TDS concentration at the interface between the saturated and unsaturated zones beneath the center of the solid waste disposal site was taken as the reference concentration. All concentrations in the study domain were expressed as non-dimensional ratios of the reference TDS value.

(b) Time (t)

The concentration of the pollutants in the study domain is a function of time, until steady-state conditions are reached. Three time stages were considered in each parametric study contained herein:

(i) The buildup stage: In this stage the leachate pollutants are continuously migrating from the bottom of the solid waste disposal site and into the ground water system.

(ii) The steady-state stage: In this stage the flux of the leachate pollutants which entered any element of volume in the subsurface is equal to the amount of the flux leaving the element.

(iii) The recovery stage: The source of leachate pollutants was extinguished by some external action (due to a dry period, shielding of the site, or collecting the leachate).

(c) Space Coordinates X, Y, and Z

X is taken as the major axis in the direction of ground water flow, Y is the lateral coordinate in the horizontal domain, and Z is the normal coordinate in the vertical domain. All distances used in this study were nondimensional ratios of the length of the solid waste disposal site in the direction of the ground water flow (L). Incremental distances (x, y and z) used in the computational scheme were selected according to site physical geometry and the conditions necessary to insure stability of the solution.

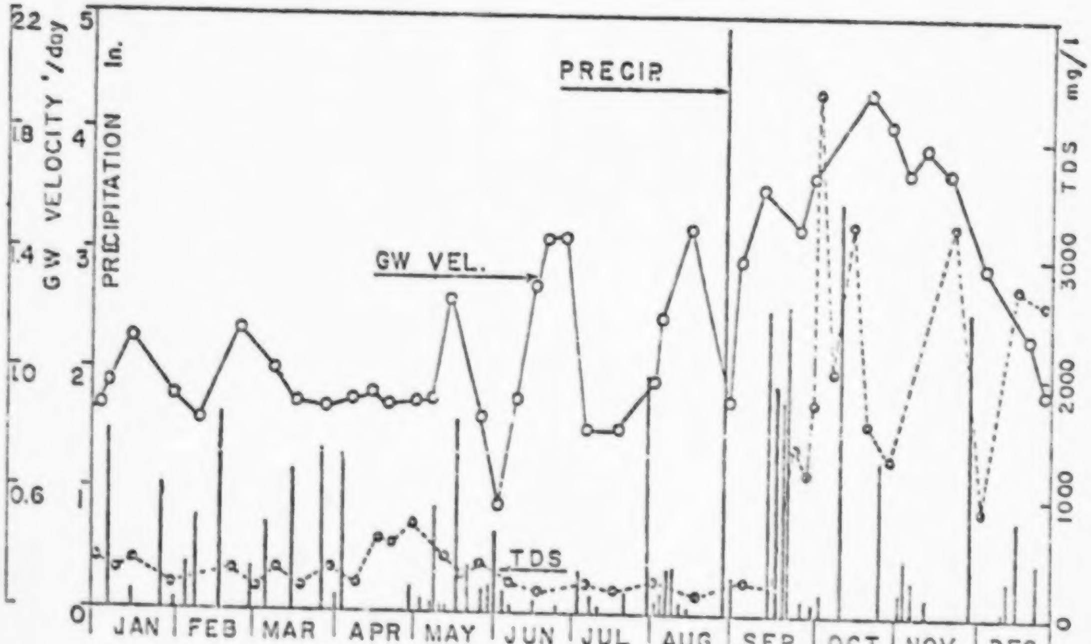
(d) The Directional Diffusion Coefficient Dx, Dy and Dz

These diffusion coefficients were found to be a function of both the molecular diffusion coefficient and the velocity of ground water flow. Many studies were done on the nature and magnitude of these coefficients (17, 18, 19, 20, 21). There is nearly unanimous agreement that the effective-diffusion coefficient in the direction of ground water flow is nearly proportional to the first power of the flow velocity, while the lateral diffusion coefficient is of the same order of magnitude of the molecular diffusion coefficient. In this study the effective diffusion coefficients were determined by the results obtained by application of typical leachate to five different soil types representing the layers in which the leachate pollutants would move.

The range of values of the effective diffusion coefficients used in this study were generated by adopting the range of infiltration velocities and ground water flow velocities shown in Figure 183. The lateral diffusion coefficients were kept constant and equal to the molecular diffusion coefficient, while both the effective longitudinal and normal diffusion coefficients were taken as linearly proportional to the ground water velocity and the infiltration velocity respectively.

(e) The Chemical Reaction Coefficient (K)

The chemical reaction term that appears in the equations was expressed as a linear function of the concentration at each point. The chemical reaction is considered in the adsorptive rather than the desorptive sense. In other words, it represents the capacity of the soil particles to remove a fraction of the leachate pollutant by adsorption or exchange of ions on the soil particles' surface. It is very difficult to determine



KENNETT SQUARE HYDROLOGIC DATE FOR 1971

FIGURE 183

a single value for this coefficient because it is a complex function of the following factors:

(i) Soil's physical properties such as particle size, shape, and gradation.

(ii) Soil's chemical properties such as base-exchange capacity, type, and concentration of ions adsorpted to the soil surface.

(iii) Leachate-ground water physical interactions. This was considered governed by physical parameters such as temperature, viscosity, pressure and rate of flow of each leachate, and the ground water.

(iv) Leachate-soil chemical interaction. This was considered governed by both the soil's and leachate's chemical properties, such as population and density of the ions present in each media, the availability of adsorption or exchange sites, and the hydrogen ion concentration.

A wide range of typical values of K were selected based on experimental determination of removal capcity by different soils for different ions present in a leachate water system.

Discussion of Parametric Analysis for the Horizontal Domain

Numerical solutions were analyzed for different parameters of leachate-ground water systems for a horizontal profile. Results of this analysis are presented in Figures 184 and 191.

Time and Space Increments -

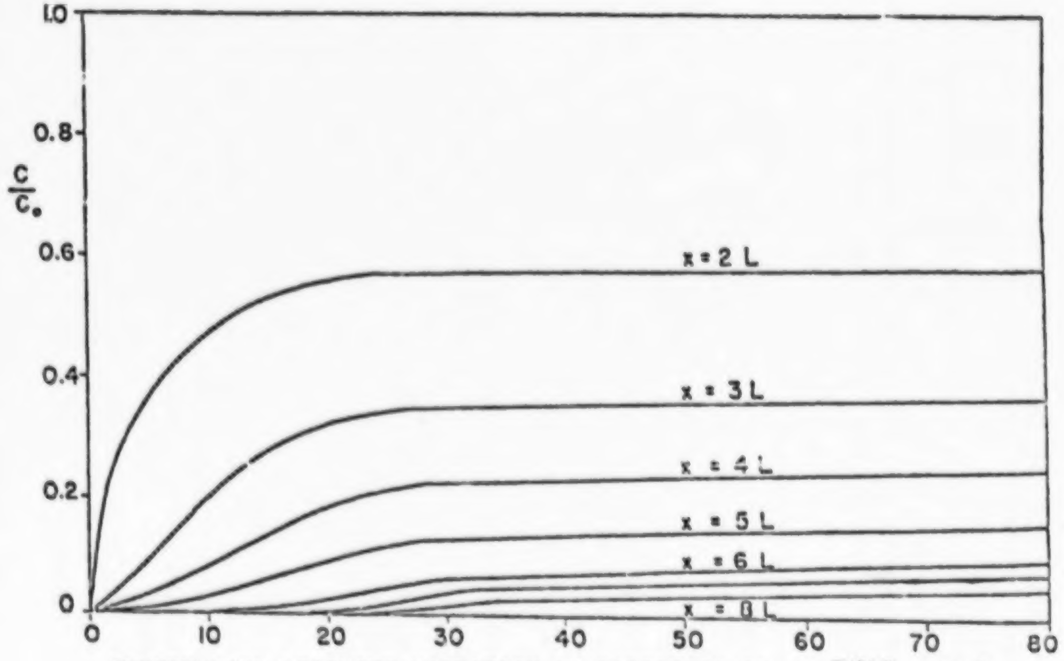
$\Delta t = \tau = 1$ day, $x = h = L$ and $y = k = L/5$

Fixed Parameters -

$Dx = 2.0$ ft^2/day (.186 m^2/day, $Dy = o.2$ ft^2/day (.0186 m^2/day), and $u = 0.5$ ft/day (.15 m/day)

Variable Parameters -

$x = -10L$ to $20L$, $y = 0$ to $6L$, $\tau = 0$ to 75 days, and $K = -0.05$ to 0.5 day^{-1}



THEORETICAL LEACHATE MIGRATION IN DIRECTION OF FLOW

FIGURE 184

K Parameters -

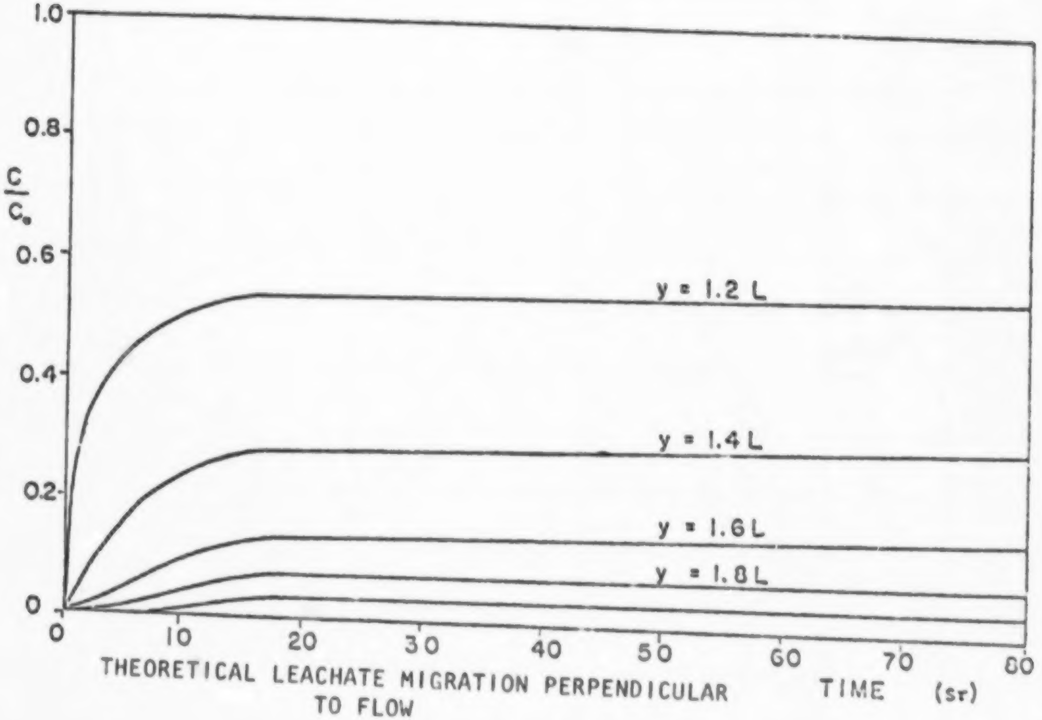
Run 1-1, K = 0.05 day^{-1}
Run 1-2, K = 0.1 day^{-1}
Run 1-3, K = 0.2 day^{-1}
Run 1-4, K = 0.3 day^{-1}
Run 1-5, K = 0.4 day^{-1}
Run 1-6, K = 0.5 day^{-1}
Run 1-1-1, K = 0.05 and leachate polluting source stopped at S = 20 days.

To investigate the time necessary to achieve steady-state in the aquifer, the leachate source was kept continuous in Runs 1-1 to 1-6. Steady-state conditions were reached after 24, 30, 35, 40, 50 and 60 time intervals for sections located at longitudinal distances of 2L, 3L, 4L, 5L, 6L and 7L downstream from the center of the simulated source respectively (Figure 184). In this study each time interval was equal to 1 day.

The buildup in concentrations for lateral sections continued until steady-state conditions were reached after 15, 18, 22, 25 and 30 time intervals for sections located at lateral distances of 1.2L, 1.4L, 1.6L, 1.8L and 2L away from the center of the site respectively (Figs. 185 and 186). In both the longitudinal and lateral migration of pollutants in the aquifer, higher concentrations were found at closer distances from the site and the pollution levels dropped sharply for sections at greater distances from the center of the site.

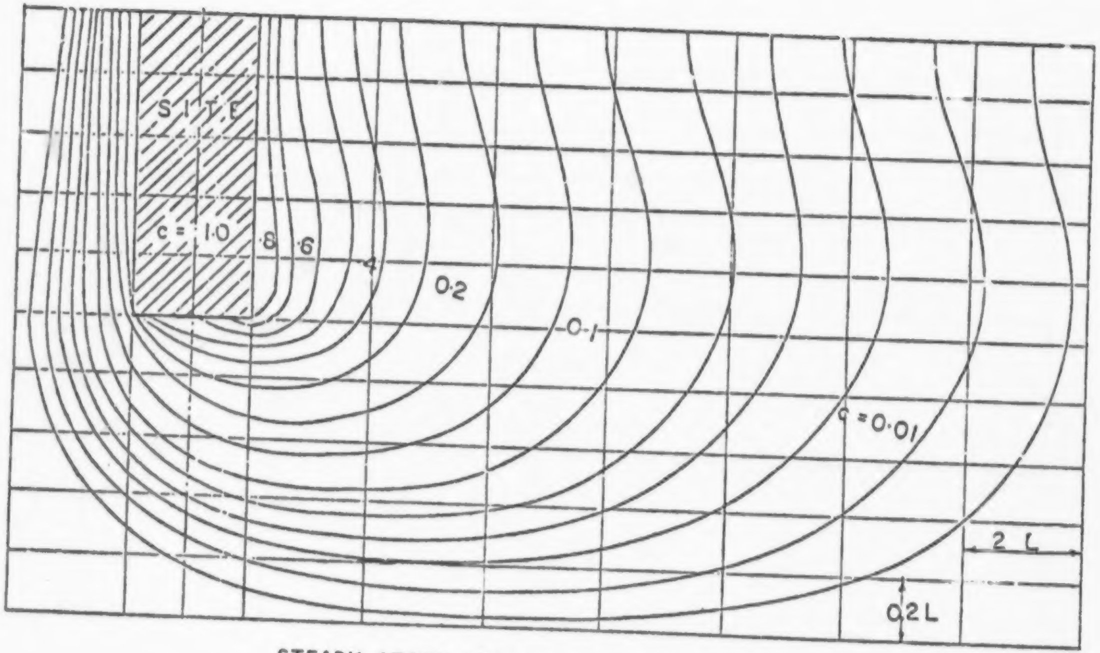
A horizontal leachate pollution migration profile at the interface between the saturated and unsaturated zones is shown in Figure 187. Concentration of the leachate pollutant substance was taken beneath the site boundaries and was assumed to be uniform and equal to unity. All concentrations in the study domain were expressed as fractions of the reference concentration. Two different scales for longitudinal and lateral directions were used to allow for reasonable spacings between isoconcentration lines. Leachate-pollutant-travel in the lateral direction was less than 4% of its travel downstream. Concentrations less than 10% of the reference concentration appeared up ground water gradient from the site, but their movement was limited to the immediate vicinity of the site. This was attributed to the molecular diffusion that could cause pollutant migration in a direction opposite to ground water velocity gradients.

Changes in the steady-state isoconcentration lines for different values of longitudinal and lateral distances showed that the peak concentration of leachate pollutant profiles shifted downstream away from the edge of the disposal site for sections located at greater distances in the lateral direction (Figure 188). Concentration profiles decreased rapidly with distance from the site and approached a limit.



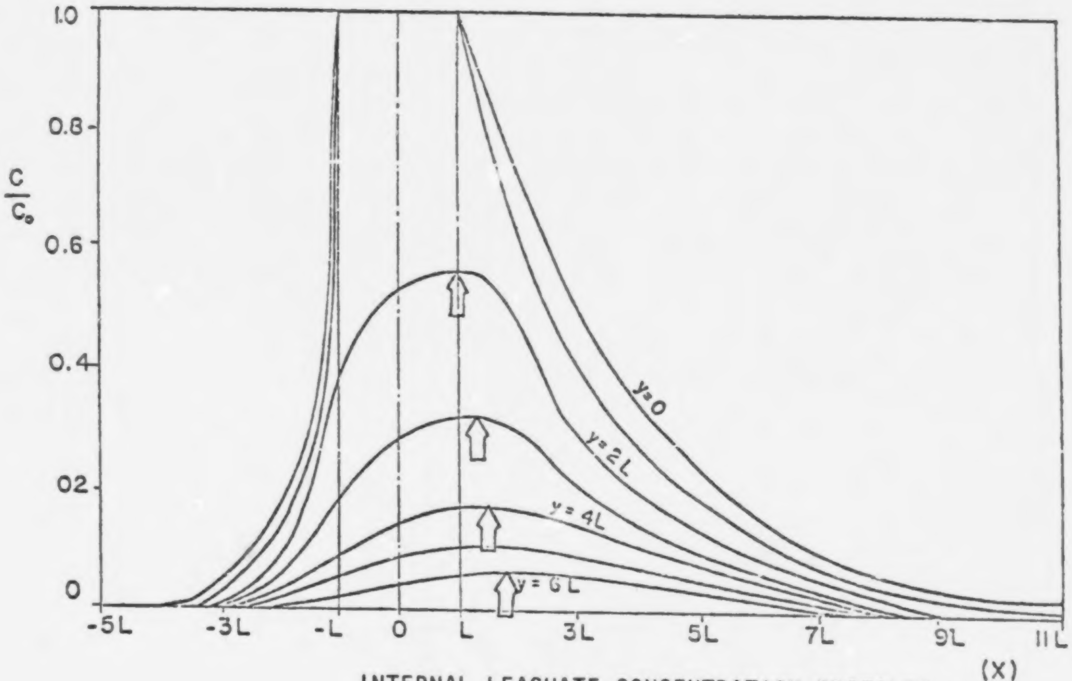
THEORETICAL LEACHATE MIGRATION PERPENDICULAR TO FLOW

FIGURE 185



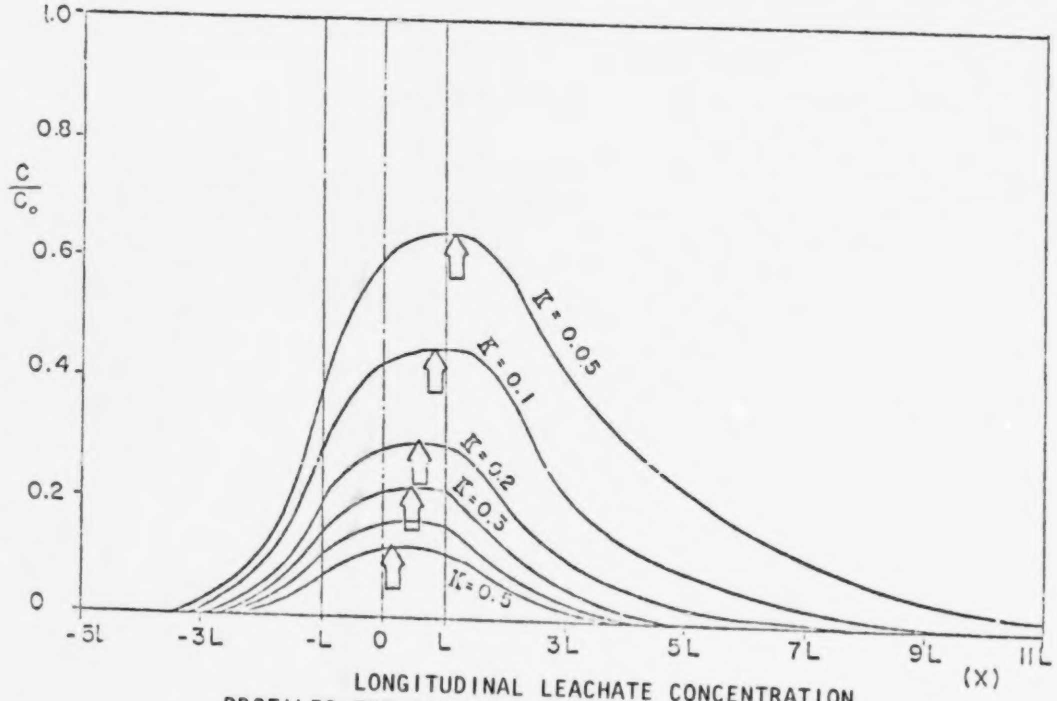
STEADY STATE LEACHATE ISOCONCENTRATION CURVE

FIGURE 186



INTERNAL LEACHATE CONCENTRATION PROFILES

FIGURE 187



LONGITUDINAL LEACHATE CONCENTRATION
PROFILES FOR GIVEN CHEMICAL REACTION COEFFICIENTS K
FIGURE 188

Steady-state concentration profiles for increasing values of the linear-chemical reaction coefficient (K) varying between 0.05 - 0.5 day^{-1} for a fixed lateral position of 1.2L are presented in Figure 189. Chemical reaction had a retarding effect on the pollutants' concentration profiles: as (K) was increased, all concentration levels were reduced, but with a decreasing rate. The peaks of the concentration profiles shifted back towards the center of the sites for higher values of (K). In other words, skewness of the concentration profiles and the travel of pollutants downstream were reduced. Also, for increasing lateral distances from the site, the pollutants' concentration levels were retarded as K increased. The shape of the pollution profiles was not affected by changing the value of the chemical-reaction coefficient.

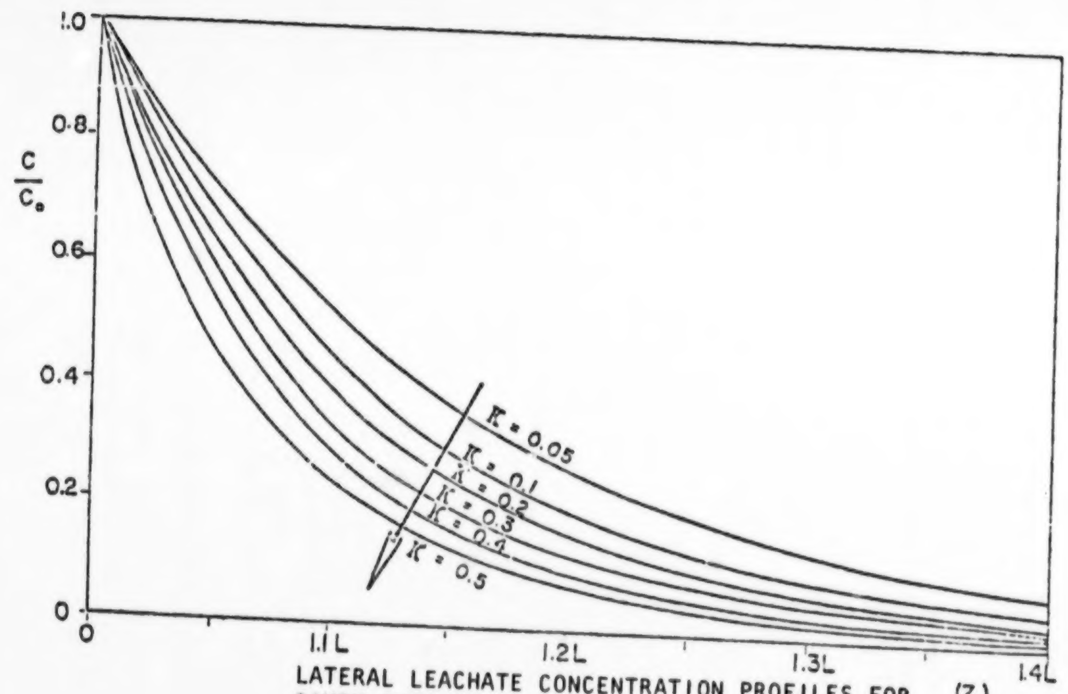
A family of concentration curves has been developed for increasing time after termination of the leaching process (Figure 190). Recovery curves are more pronounced beneath the site and in its immediate vicinity, while concentration buildup is present at distances larger than 4L downstream from the site. In both buildup and steady-state stages, peak concentrations occurred beneath the boundaries of the site, but in the recovery stage, the peak concentrations shifted in the direction of flow as recovery time progressed. It should be noted that the ground water system needed more time to recovery from the imposed pollution load after termination of the source than was required for the buildup to the same concentration levels. This behavior is caused by the nature of the irreversible chemical reaction and asymmetry of the flow system. When the recovery stage had progressed for 5 time intervals, all concentrations were dropped in both longitudinal and lateral directions (Figure 191). Peak concentrations of the leachate pollution curves shifted closer towards the site for points located at greater lateral distances. This behavior is opposite to the buildup patterns presented in Figure 187.

Discussion of Parametric Analysis for the Vertical Domain

Numerical solutions were analyzed for different parameters of a leachate-ground water system for a vertical profile. Results of this analysis are presented in Figures 192 and 202.

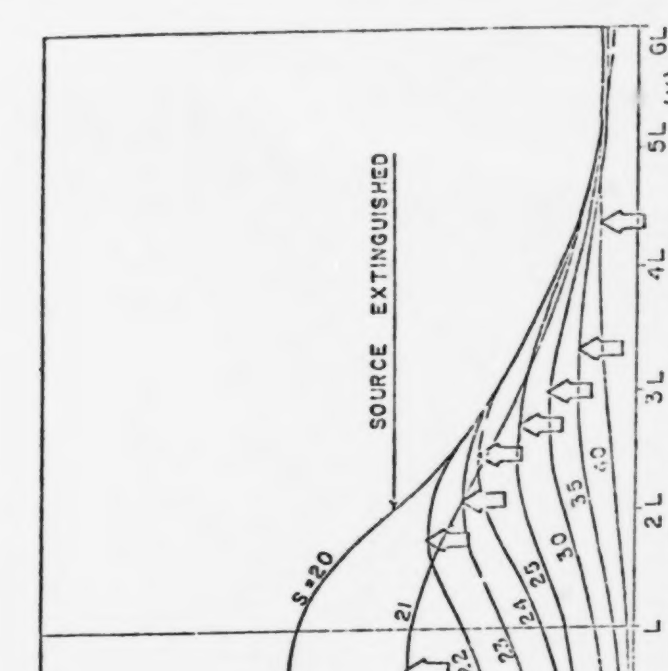
Time and Space Increments -

$\Delta t = \tau = 1$ day, $x = h = L$, and $z = k = L/5$.



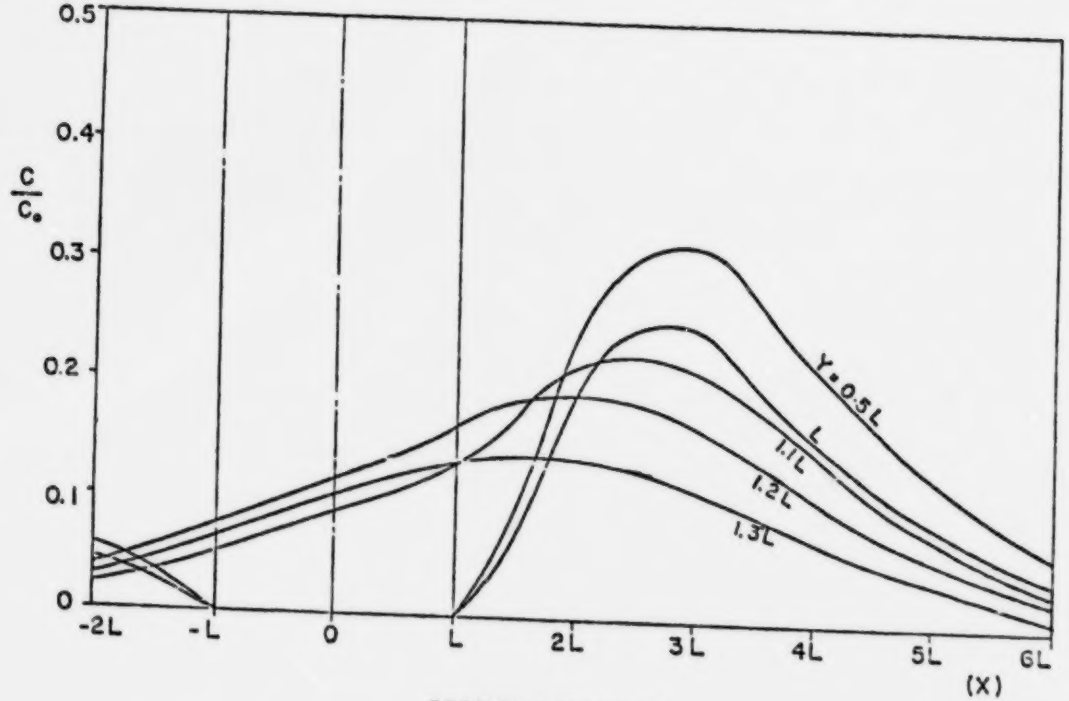
LATERAL LEACHATE CONCENTRATION PROFILES FOR GIVEN CHEMICAL REACTION COEFFICIENTS K

FIGURE 189



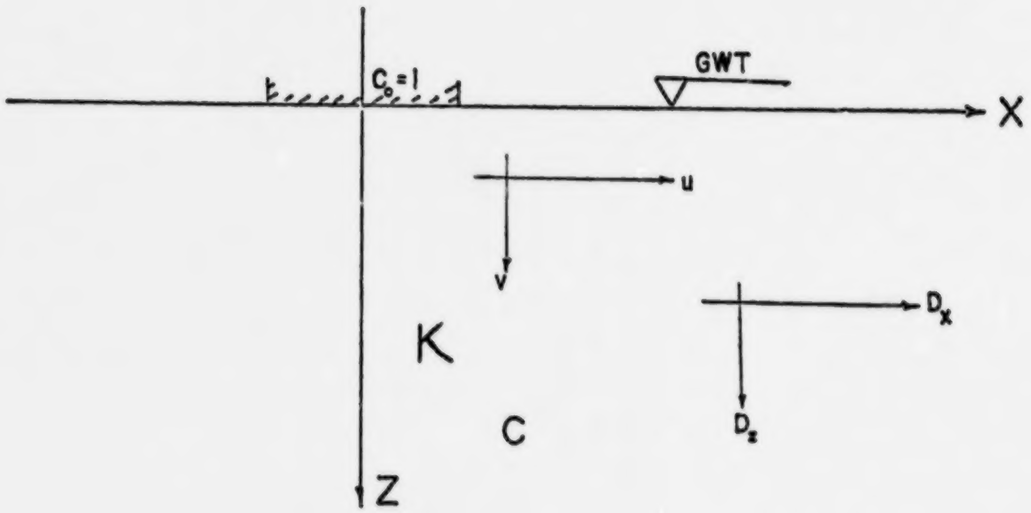
RECOVERY PATTERN AFTER STOPPAGE OF LEACHATE INPUT

FIGURE 190



RECOVERY PROFILES

FIGURE 191



TWO-DIMENSIONAL SIMULATION AND SITE PARAMETERS IN THE X-Z DOMAIN
FIGURE 192

Fixed Parameters -

$Dx = 0.2$ ft^2/day, $K = 0.05$ day^{-1}, and $w = 0.05$ ft/day.

Variable Parameters -

$x = -10L$ to $20L$, $z = 0L$ to $6L$, $t = 0$ to 75 days
$u = 0.05$ to 1.0 ft/day, and $dx = 0.2$ to 4.0 ft^2/day.

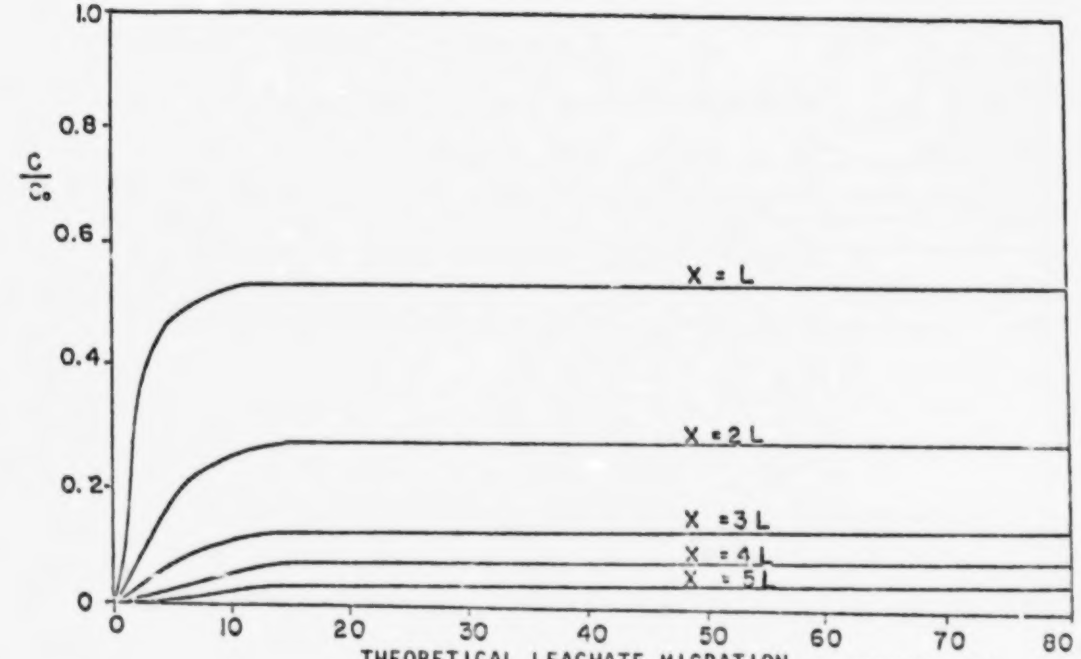
K Parameters -

Run 2-1	$u = 1.0$ ft/day,	$Dx = 4.0$ ft^2/day
Run 2-2	$u = 0.7$ ft/day,	$Dx = 2.8$ ft^2/day
Run 2-3	$u = 0.5$ ft/day,	$Dx = 2.0$ ft^2/day
Run 2-4	$u = 0.2$ ft/day,	$Dx = 0.8$ ft^2/day
Run 2-5	$u = 0.1$ ft/day,	$Dx = 0.4$ ft^2/day
Rum 2-6	$u = 0.05$ ft/day,	$Dx = 0.2$ ft^2/day
Run 2-1-1	$u = 1.0$ ft/day,	$Dx = 4.0$ ft^2/day

Source is stopped at $S = 20$.

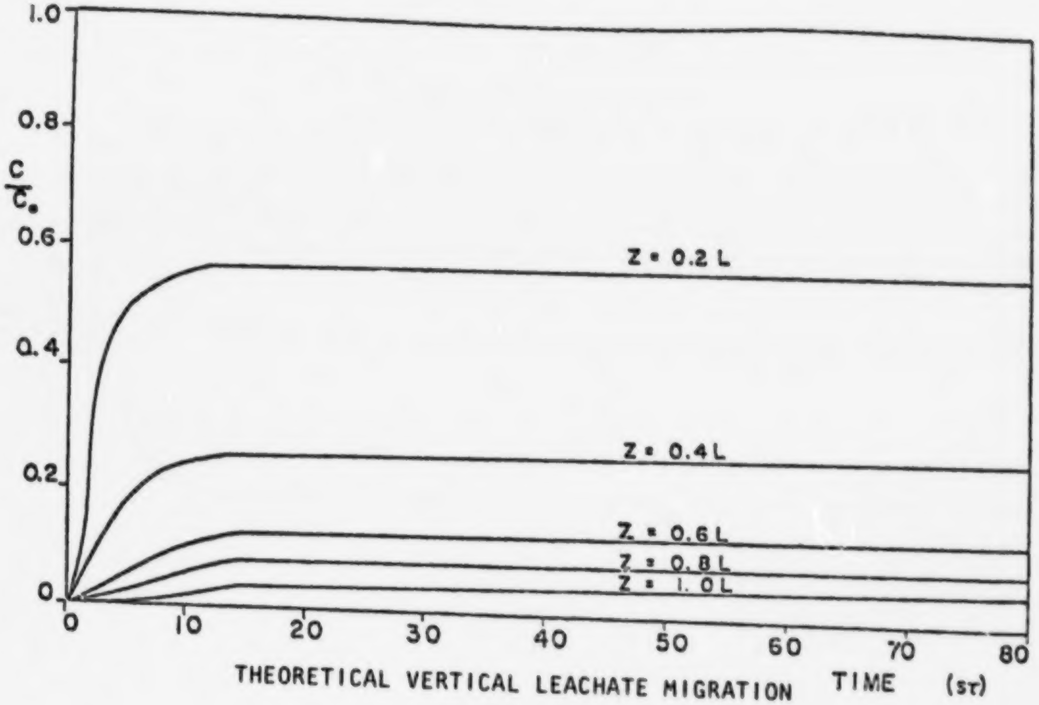
The buildup in leachate pollution levels continued until steady-state conditions were reached after 11, 15, 17, 20 and 25 time intervals (one time interval is equal to one day) at longitudinal distances of 1L, 2L, 3L, 4L and 5L away from the center of the site. In all cases leachate pollutant concentration levels at points closer to the site were higher leachate pollutant concentrations than levels at points farther away. However, the separation between successive concentration profiles decreased at greater distances downgradient (Figure 193). In the direction of ground water flow, the buildup in pollution levels increased to a maximum after 12, 13, 17, 20 and 25 time increments for depths below ground water of 0.2L, 0.4L, 0.6L, 0.8L and 1.0L. In all cases the leachate pollutant concentration levels at shallower depths were higher than those at greater depths. However, distance between successive leachate pollutant concentration curves decreased at the greater depth (Figure 194).

Vertical pollution profiles for an unconfined ground water system underlying the solid waste disposal site are shown in Figure 195. Leachate pollution concentration levels are presented as isoconcentration profiles using a reference concentration at the ground water table under the center of the site. Spacings between successive leachate pollution isoconcentration curves increased with increasing distance from the solid waste disposal site in both the directions of ground water flow and vertically. Two different scales were used for the horizontal and vertical grid to control the spacing of the isoconcentration curves. Points of



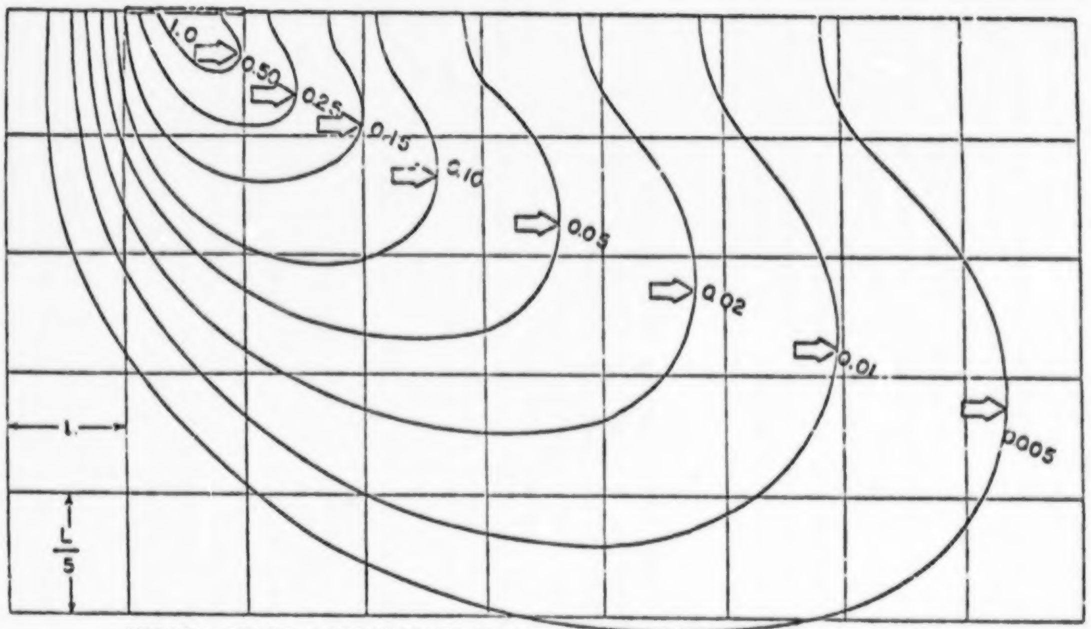
THEORETICAL LEACHATE MIGRATION
IN DIRECTION OF FLOW

FIGURE 193



THEORETICAL VERTICAL LEACHATE MIGRATION

FIGURE 194



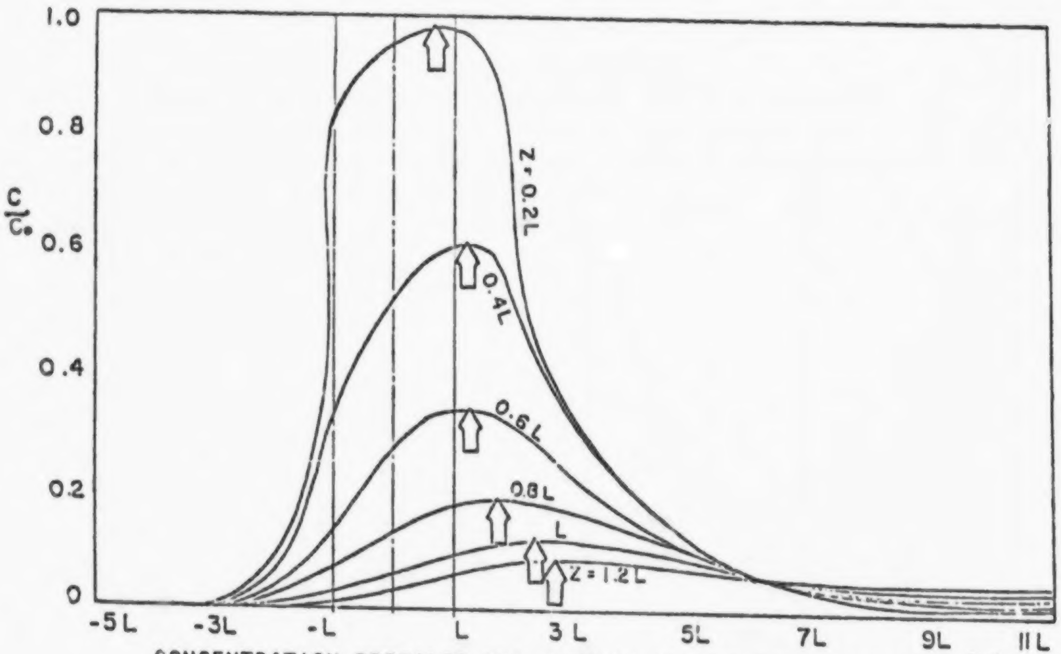
STEADY STATE ISOCONCENTRATION LINES IN THE VERTICAL DOMAIN

FIGURE 195

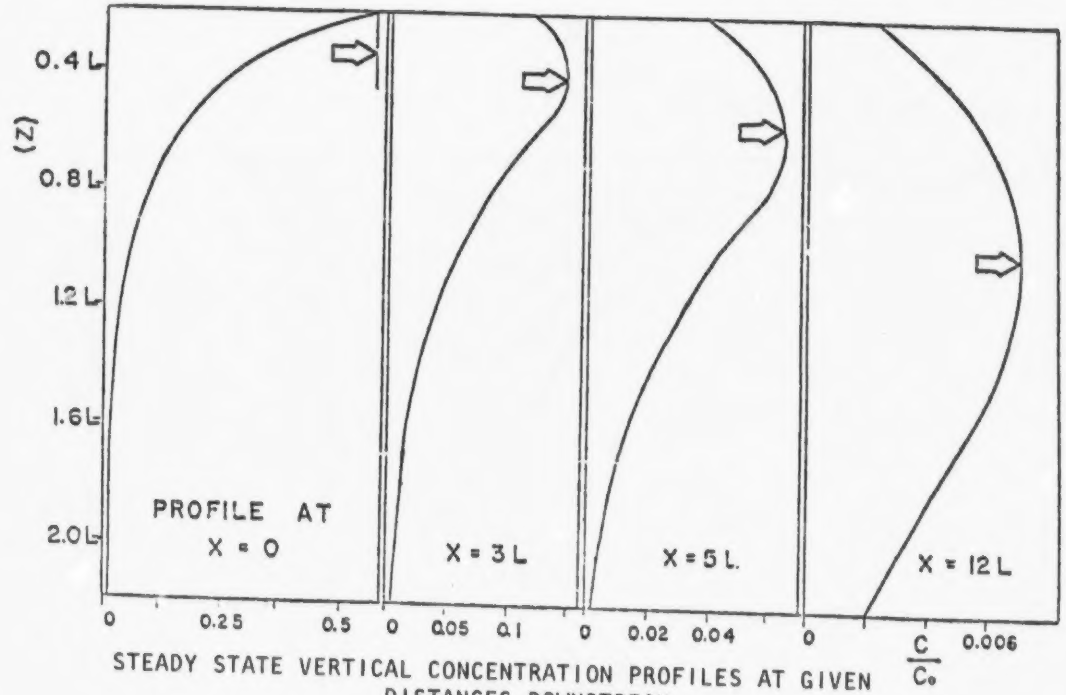
tangency of isoconcentration curves corresponding to points of maximum concentration at any particular location, increased with depth at greater distances downgradient from the site. Isoconcentration curves of less than 0.1 of the reference concentration occurred upgradient from the site. However, the leachate pollutants migrated upgradient only very small distances. Movement away from the solid waste disposal site in the direction of ground water movement, or in the direction of leachate movement, decreased the pollutants' concentration (Figure 196). Peak concentrations on the leachate pollutant concentration curves kept shifting in the direction of ground water flow as the depth increased. Leachate pollutants concentration curves at different points of successively increasing distances in the direction of ground water flow are shown in Figure 197. The leachate pollutant concentrations were reduced and their peaks were shifted to greater depths with increasing distance from the source site. This would appear as inversions in concentration profiles downgradient from the solid waste disposal site.

The major effect of increasing the ratio of ground water to leachate infiltration velocity (u/w) is reduction of leachate pollution concentration levels beneath the solid waste disposal site and in its immediate vicinity. Conversely, higher u/w ratios caused higher leachate pollutant concentration levels at increasing distances downgradient (Figure 198). For low u/w ratios the shapes of the concentration curves are more symmetrical about the centerline of the solid waste disposal site, and they approximate Gaussian normal distribution curves. For large u/w ratios the shape of the leachate pollutant concentration curves is more skewed in the direction of ground water movement. This behavior pattern indicates that for relatively high ground water velocities, leachate pollutant concentration levels in the vicinity of the solid waste disposal site will be lowered, but relatively higher concentrations will appear at greater distances downstream. For the lateral directions (Figure 199) for higher u/w ratios, pollutants-concentration profiles were reduced at all depths.

Changes in the 0.25 isoconcentration line for different values of the ratio of the ground water velocity to the leachate infiltration velocity at steady-state conditions are shown in Figure 200. For low u/w ratios, isoconcentration curves were more skewed in the direction of ground water motion and had a flatter shape. This indicates that for relatively high ground water velocities, pollutants travel larger distances downstream but at shallower depths. Peaks of isoconcentration curves were shifted vertically

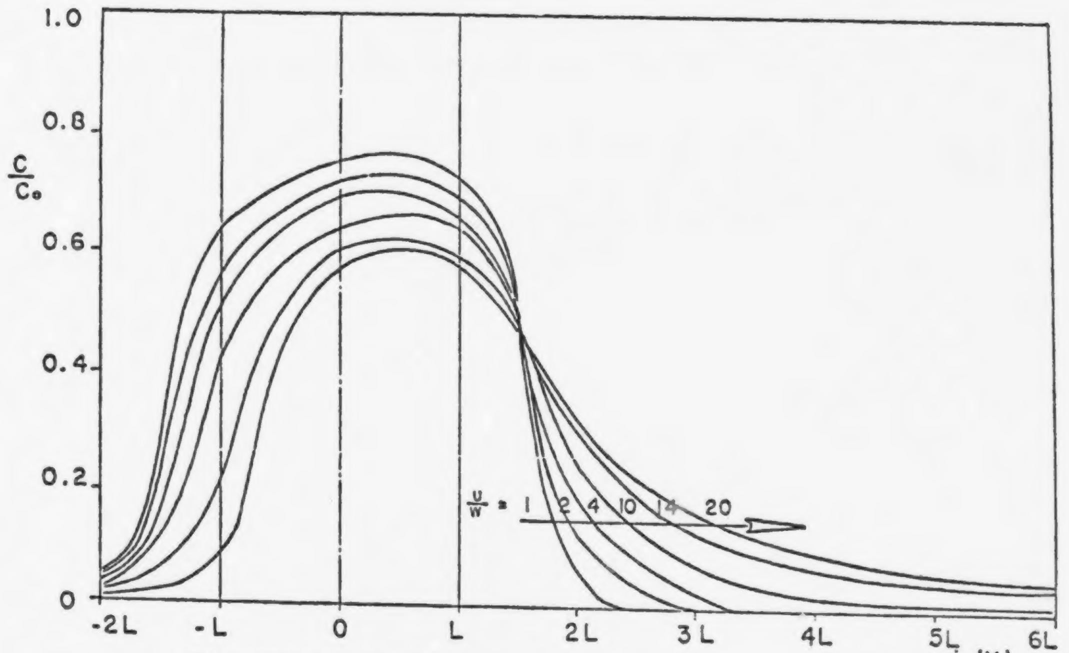


CONCENTRATION PROFILES FOR VARYING DEPTHS BELOW GROUND WATER TABLE
FIGURE 196



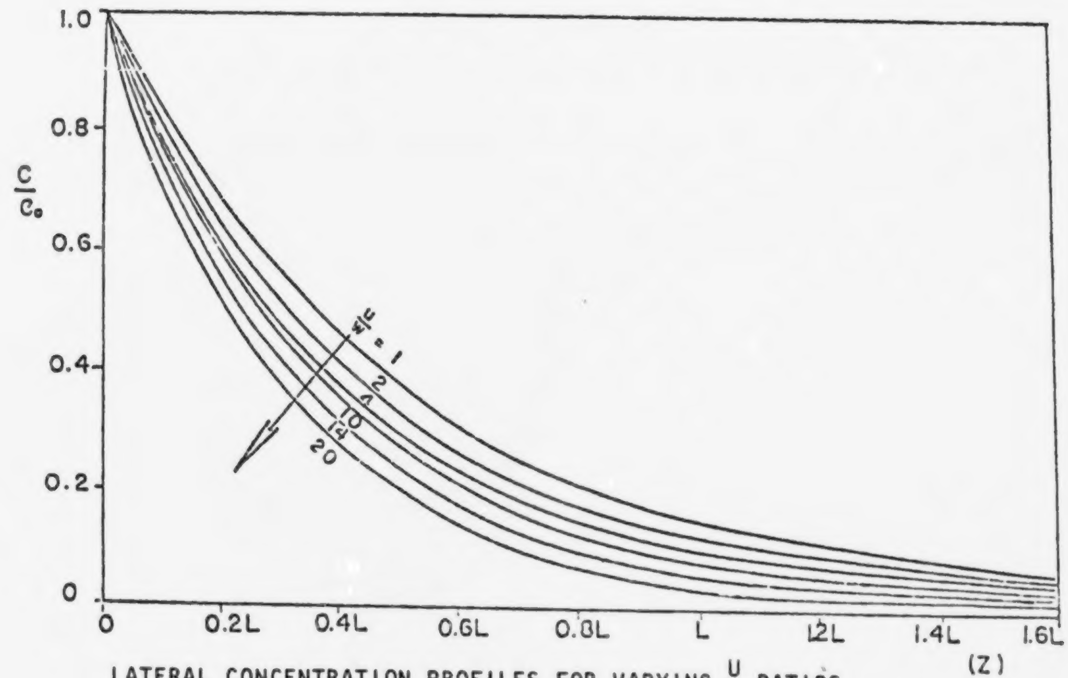
STEADY STATE VERTICAL CONCENTRATION PROFILES AT GIVEN DISTANCES DOWNSTREAM

FIGURE 197



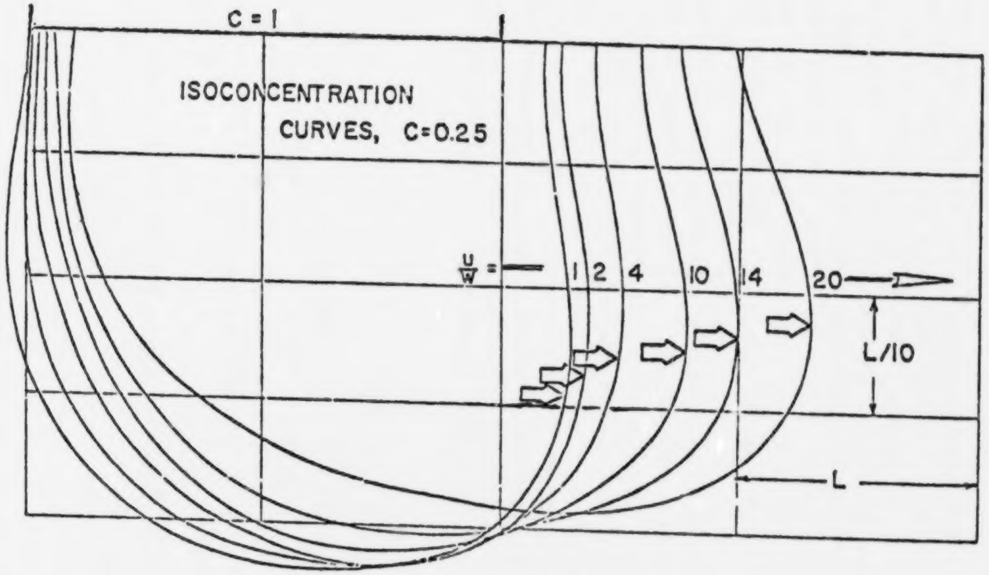
LONGITUDINAL CONCENTRATION PROFILES FOR VARYING $\frac{U}{W}$ RATIOS

FIGURE 198



LATERAL CONCENTRATION PROFILES FOR VARYING $\frac{U}{W}$ RATIOS

FIGURE 199



$\frac{U}{W}$ RATIO EFFECT ON LEACHATE MIGRATION

FIGURE 200

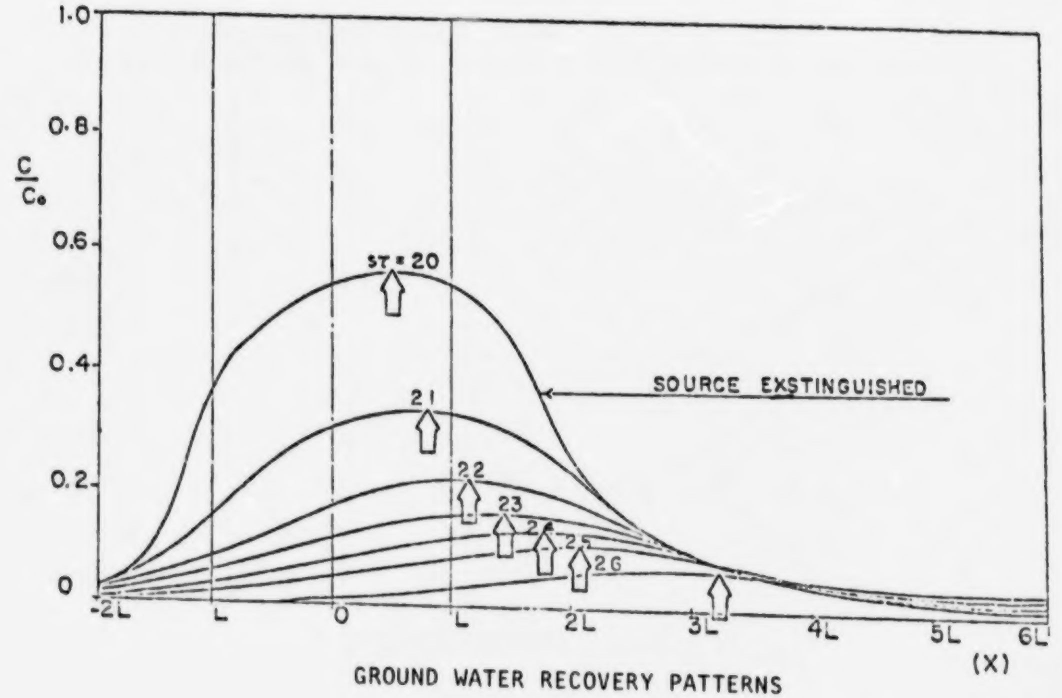
up as the ratio of u/w was increased. This pattern suggests that inversion points on depth-concentration curves will be observed at shallower depths for relatively high ground water velocities.

To study the recovery pattern of an unconfined ground water system (Fig. 201), the leachate source was terminated after 20 time intervals. The concentrations beneath the solid waste disposal site and in its immediate vicinity dropped at a rapid rate immediately after termination of the source and then at a slower rate. At the same time leachate pollutant concentration levels' greater distances stayed constant or decreased at slower rates with increasing time. Further, the concentration curve peaks kept shifting downstream away from the source with increasing time. This pattern suggests that in the recovery stage the pattern of leachate pollution concentration levels is the reverse of that in the buildup stage. This behavior would result in the appearance of higher leachate pollutant concentration levels at greater distances from the solid waste disposal site. After 5 days of recovery, leachate pollutant concentration levels were lower at greater depths with an inversion occurring above the 0.4L depth (Figure 202). The peaks of leachate pollutant concentration curves moved away from the disposal site as the depth increased. This pattern shows that at greater depths the highest leachate pollutant concentration will appear at further distances downstream from the solid waste disposal site.

Conclusions of the Parameter Study

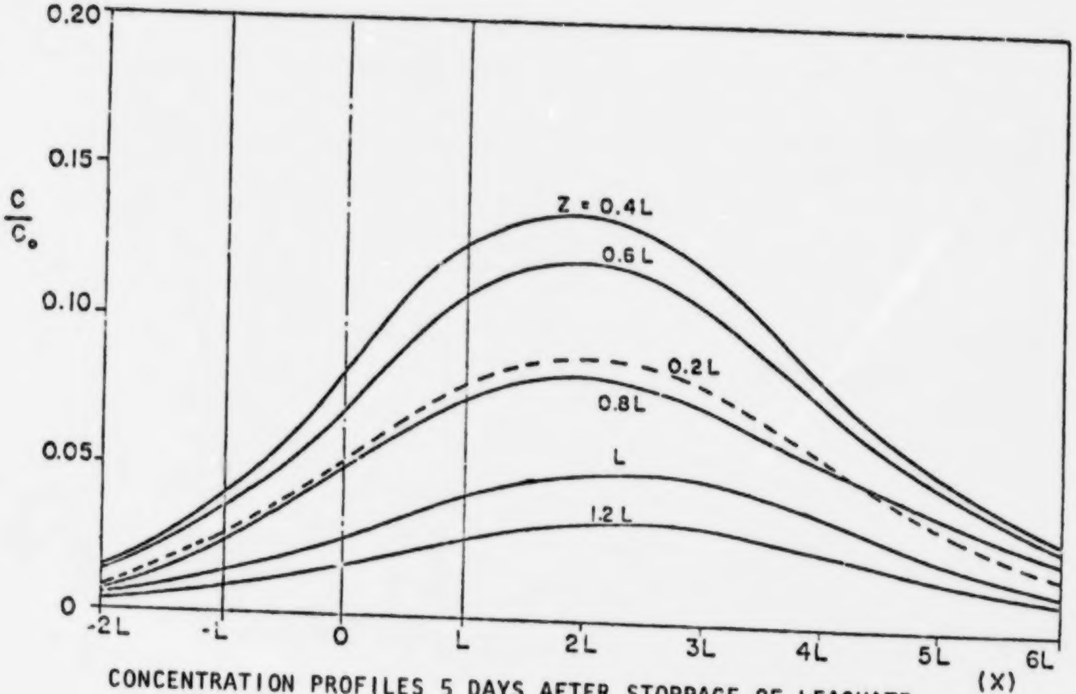
(a) Steady-state conditions for leachate pollutant concentration levels are reached when the leachate source is continuous. Maximum values are reached after longer time periods the further the distances from the solid waste disposal site.

(b) The leachate pollutant isoconcentration curves extend to greater distances in the direction of ground water flow, but they extend to minor distances in both the lateral and vertical directions. This pattern indicates that for the range of parameters used in this study, the dispersion of pollutants due to velocity convection is the major mechanism to leachate pollutant migration away from the site. The spacings between successive isoconcentration curves decreased more rapidly at greater distances away from the solid waste disposal site. This pattern suggests that ground water pollution will be highest in the immediate vicinity of the site than further away.



GROUND WATER RECOVERY PATTERNS

FIGURE 201



CONCENTRATION PROFILES 5 DAYS AFTER STOPPAGE OF LEACHATE INFILTRATION INTO GROUND WATER

FIGURE 202

(c) In the horizontal domain, for both the buildup and steady-state stages, the highest concentrations were found directly beneath the disposal site. Leachate pollutant concentration levels decreased with increasing distances downgradient from the site. In the vertical domain, higher leachate pollutant concentrations were found at locations close to the site, but peak concentrations at different locations were found only at the ground water table within the boundaries of the disposal site. At vertical sections further downgradient, leachate pollutant peak concentrations were found at greater depths. However, the magnitude of the peaks decreased with increasing distances. This pattern appears as an inversion in the concentration curves.

(d) In the recovery period, for both the horizontal and vertical domains, the maximum leachate pollutant concentration levels moved from under the solid waste disposal site. The peak concentrations migrated from the site with increasing recovery time until complete die-off occurred. The shape of the recovery curves results primarily from dispersion and dilution of the existing leachate pollutants. The time of recovery from certain leachate pollutant levels was significantly higher than the time of buildup to the same level.

(e) The removal of leachate pollutants from the ground water by chemical reaction with the soil and adsorption on the soil surface is defined by the coefficient of chemical reaction (K). As this coefficient is increased, the whole leachate pollutant concentration curve is reduced in both the longitudinal and lateral directions. The shape of these curves is found to be more skewed towards the direction of flow for lower values of K. This indicates that low activity soils will permit a larger amount of pollutant-travel in both directions, while active materials such as clays will retard the travel of pollutants and confine the high pollution levels to the immediate vicinity of the site.

(f) Changes in the ratio of ground water flow velocities (u/w) greatly influences the pattern of dispersion of the leachate pollutants from a solid waste disposal site. As u/w is increased, the vertical infiltration of pollutants is reduced, while their travel in the direction of flow is continuously increased. In other words, the leachate pollutants travel at shallower depths but migrate further distances downgradient. Also, recovery patterns improve considerably with increasing u/w ratio. This observation confirms the assumption that velocity convection is the major mechanism in the mass transfer of leachate pollutants.

Correlation of Field Data with Theoretical Leachate Pollution Analysis

The average values of the TDS of the E, SF, SI, WF and WI wells have been used to evaluate the applicability of the mathematical model developed in the previous section. Because the shallow wells all were not in the direction of flow, a correction for lateral diffusion had to be included (Table 32) in the two dimensional simulation study.

The two-dimensional dispersion equation was solved numerically for the boundary values representing the Kennett Square test site with the aid of a high speed digital computer (IBM/360). The distances were taken as non-dimensional ratios of the landfill length in the direction of ground water flow. Concentrations were defined in the form of non-dimensional ratios to the concentration at a reference point located right beneath the center of the site at the ground water table. Typical field velocities were taken as established previously.

A plot of theoretical and field measured concentrations is shown in Figures 203 and 204.

The predicted TDS values for different wells at different depths below the ground water table were generated from the solution of the dispersion equation in the vertical domain. These leachate pollutant concentration levels are for a section taken at the center line of the site, and are not corrected for lateral dispersion.

The solution of the dispersion equation in the horizontal domain was used to generate correction factors for the lateral dispersion in the vertical domain. The values of the correction factors are a function of the longitudinal distance (x) and the lateral distance (y) for every set of wells. These factors are found in Table 32.

There are several facts of interest with regard to differences between the theoretical curves and the experimental data. They include:

(a) Deviations in the shape of experimental breakthrough curves from the shapes of the theoretical curves due to a decrease in soil permeability due to clogging of soil voids by finer particles. Clogging has been observed initially in soils sampled from shallower

TABLE 32

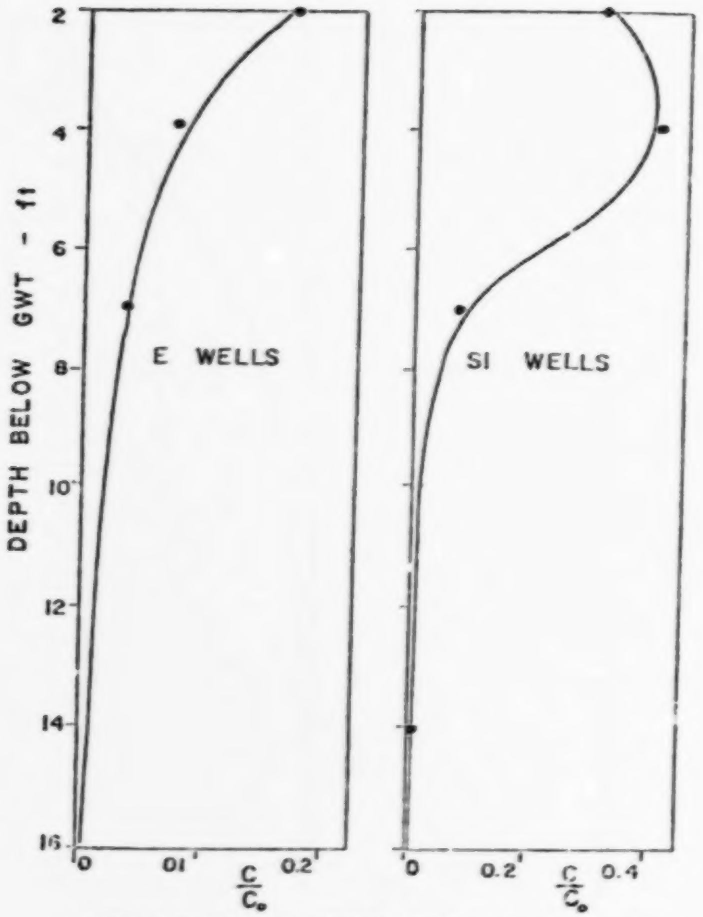
Correction Factors for Lateral Dispersion Effect on Vertical Concentration Profiles

Wells	Longitudinal Distance $\frac{X}{L}$	Lateral Distance $\frac{Y}{L}$	Correction Factor
E	0.4	1.1	0.4
SF	2.0	0.2	0.4
SI	1.3	0.0	0.8
WF	1.5	1.0	0.7
WI	1.1	0.8	0.5

TABLE 33

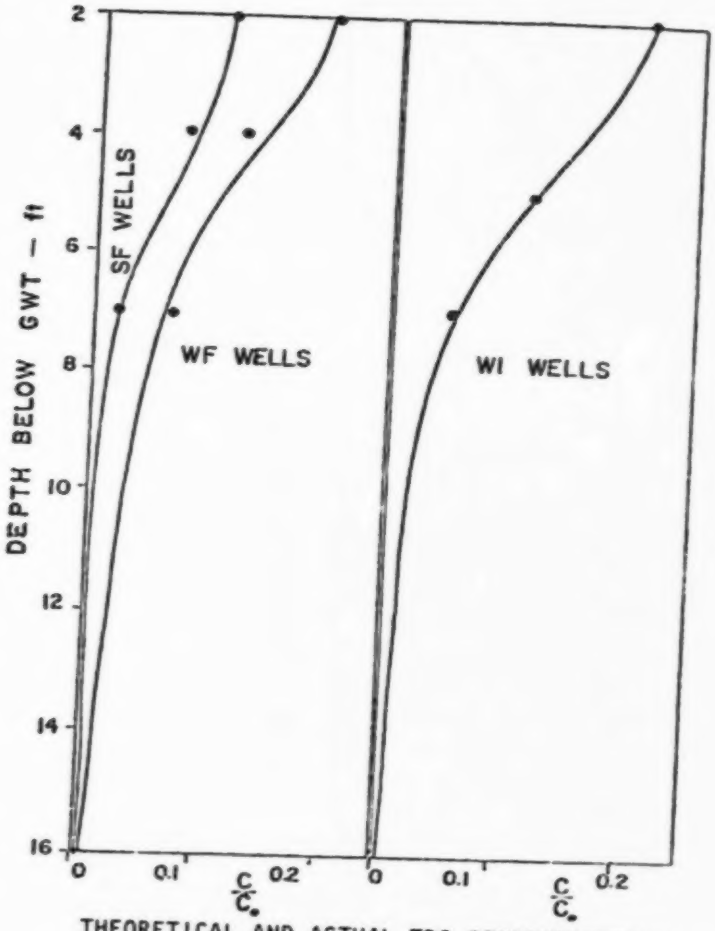
Observed and Predicted TDS Values of Test Wells

Well	Predicted TDS Before Correction	Correction Factors	Predicted TDS	Average Measured TDS
E-23	0.40	0.4	0.16	0.2
E-25	0.20	0.4	0.08	0.11
E-28	0.10	0.4	0.04	0.05
E-35	0.01	0.4	0.004	-
SI-23	0.40	0.8	0.32	0.28
SI-25	0.50	0.8	0.40	0.4
SI-28	0.10	0.8	0.08	0.06
SI-35	0.02	0.8	0.016	0.015
SF-23	0.25	0.4	0.10	0.10
SF-25	0.20	0.4	0.08	0.06
SF-28	0.10	0.4	0.04	0.04
SF-35	0.01	0.4	0.004	-
WF-23	0.25	0.7	0.18	0.21
WF-25	0.18	0.7	0.12	0.11
WF-28	0.11	0.7	0.07	0.06
WF-35	0.02	0.7	0.014	-
WI-23	0.40	0.5	0.20	0.20
WI-25	0.24	0.5	0.12	0.11
WI-28	0.10	0.5	0.05	0.05
WI-35	0.015	0.5	0.008	-



THEORETICAL AND ACTUAL TDS CONCENTRATIONS FOR WELL CLUSTERS E AND SI

FIGURE 203



THEORETICAL AND ACTUAL TDS CONCENTRATIONS FOR WELL CLUSTERS SF, WF, AND WI

FIGURE 204

depths, and last, at soils sampled from greater depths. Reduction of permeability in the top soils can be related to their higher content of organics and clay minerals which cause clogging and bridging of soil voids. Figure 205 shows a family of theoretical breakthrough curves calculated for different values of permeability. When permeability decreases with time, the theoretical breakthrough curve should follow the dotted line corresponding to actual values of permeability.

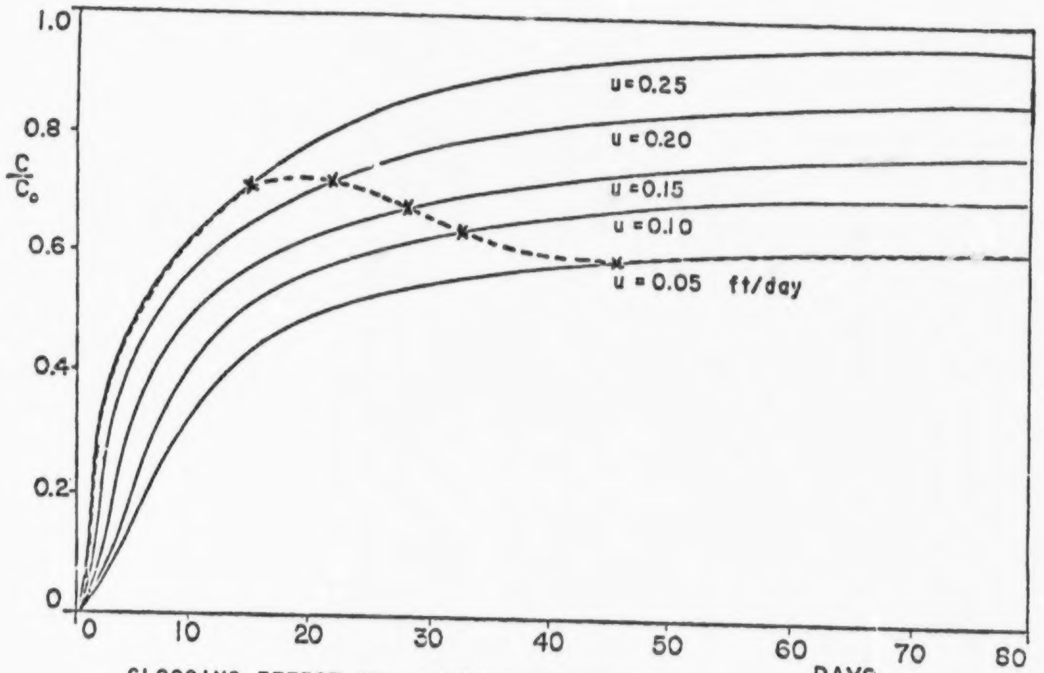
(b) Good correlation between theoretical curves and experimental field data was obtained under the following conditions:

  (i) All depths were references to the ground water table.

  (ii) Average field concentrations data was changed into non-dimensional form using an average concentration at the reference point located beneath the center of the solid waste disposal site and at the ground water table.

  (iii) Predicted pollution curves were developed using the two-dimensional model for the vertical domain including diffusion, convective dispersion and chemical reaction in the numerical solution.

  (iv) Predicted pollution profiles were adjusted using a correction factor for lateral diffusion; this factor was derived from the two-dimensional simulations in the horizontal domain for each field well location.



CLOGGING EFFECT ON LEACHATE MIGRATION

FIGURE 205

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APPENDIX

FIELD CAPACITY EXPERIMENT

Construction

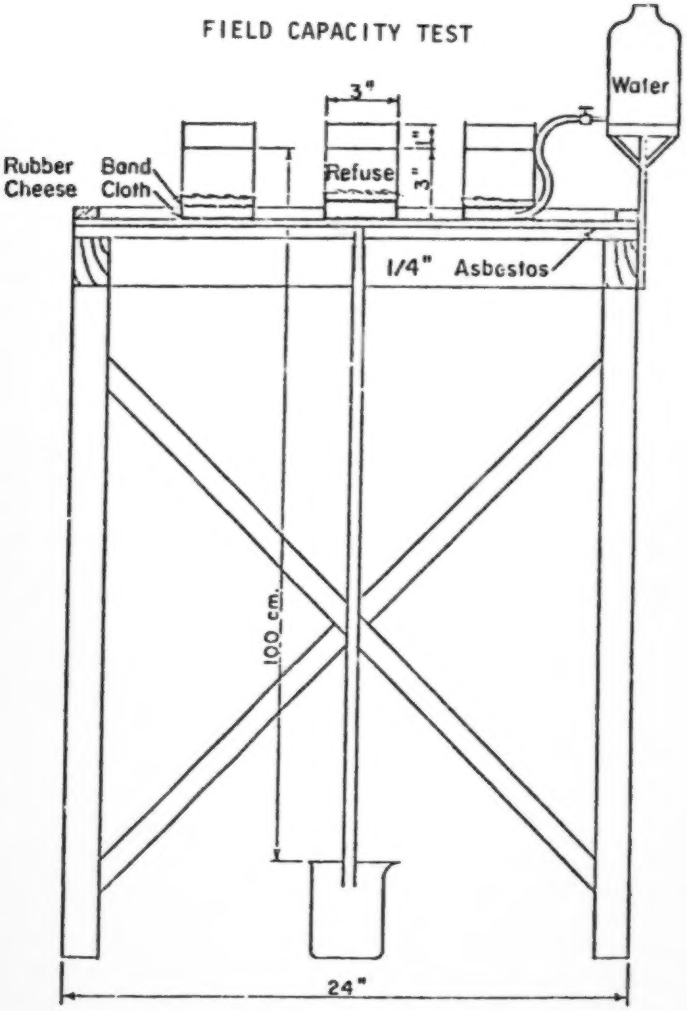
Asbestos tension tables (Fig. A-1) were used to determine the field capacities of the refuse. Brass was used for the tension tables in order to reduce corrosion. A rectangular plate 1/2 inch thick, 24 inches by 24 inches was employed. A 1/4 inch hole was drilled through the plate to allow water to drain into the tube. This water outlet was attached to a rubber hose connected to a water-leveling flask which was located 100 cm. below the top of the refuse cylinder. A piece of screen was then placed on top of the brass plate. An asbestos pad 1/8 inch thick was used as the tension membrane. The 1/8 inch thickness was selected so that the material would conduct water rapidly enough so that the refuse samples rather than the asbestos, would determine the field capacity. Tests showed that the asbestos would not allow air entry at 200 cm., but that at a tension of 100 cm. it would pass one inch of water in ten seconds. This was far greater than any value expected for the refuse.

To secure the asbestos to the screen and brass plate, a brass rectangular frame made of a 1/4 x 1/4 x 1/2 inch plate was bolted through the asbestos and onto the brass plate as the final step in construction.

Operation

When the asbestos was securely bolted to the brass plate, the frame with asbestos was immersed in deaerated water to insure complete saturation of the pad. A vacuum placed on the rubber hose drew water through the asbestos pad. The hose connection was then clamped and the membrane was uprighted and put on its stand. Water was then applied to the membrane and the open end of the hose was immersed in the flask or beaker and all air was removed from the hose before the clamp was removed. The membrane had to be kept wet at all times to insure the tension. The flask or beaker was positioned so that there were 100 cm. from the exposed water level in the flask to the top of the refuse.

FIELD CAPACITY TEST



ASBESTOS TENSION TABLE FIGURE A-1

Weighed quantities of material were then placed into the 3 inch diameter cylinders (Fig. 302) and compacted 3 inches in height. This allowed a one inch free board to the top of the cylinder. A piece of cheesecloth to keep the sample positioned in the cylinder was then secured to the bottom of the cylinder with a rubber band. These cylinders were then immersed in water for 48 hours up to the top level of the sample. This saturated the sample to insure even movement of water from the refuse when the tension of 100 cm. of water was added. The cylinders were then placed on the tension table and allowed to stand for 48 hours.

The weight of the sample plus water retained was then calculated and the sample was then dried at 100°C. The dry weight of the sample was then obtained and the water retained was then calculated (wet weight--dry weight--weight water). The dry density of the sample was then calculated (dry weight/ vol. of cylinder). Finally, the field capacity was calculated (weight of water/dry weight = percent moisture of field capacity).

Permeability Experiment

The standard constant head permeability test (Fig. A-2) described in Lambe and Whit was used to determine the permeability of the milled and unmilled refuse. The only modification required was the placing of a screen over the refuse to hold the refuse securely in place. Without this screen flotation of the refuse occurred and invalidated the results.

To insure saturation, the refuse was completely saturated before compaction in the test cylinder.

CONSTANT HEAD PERMEABILITY TEST

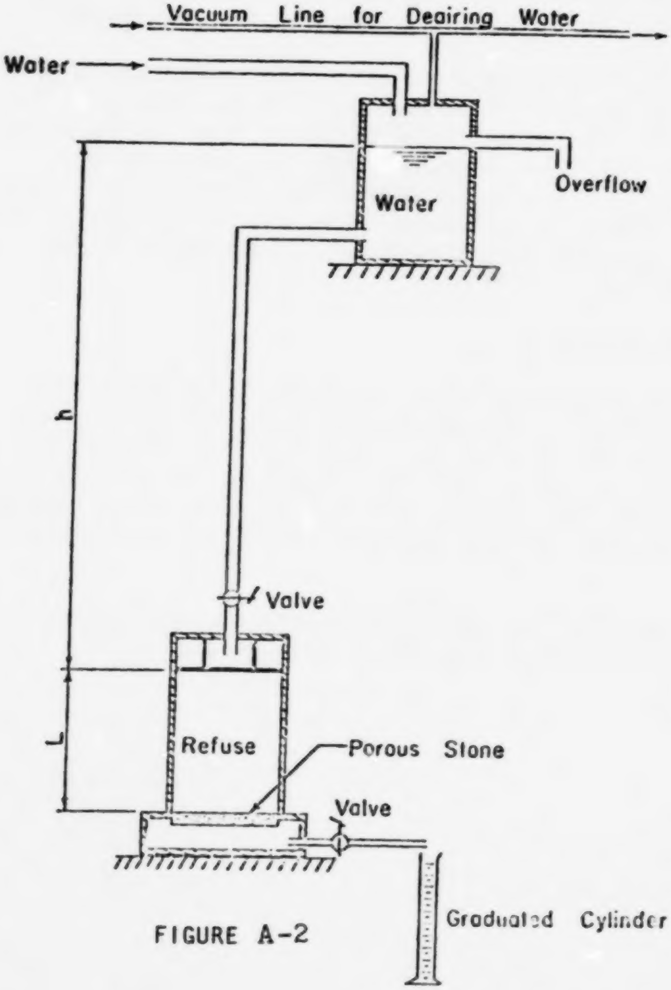


FIGURE A-2

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